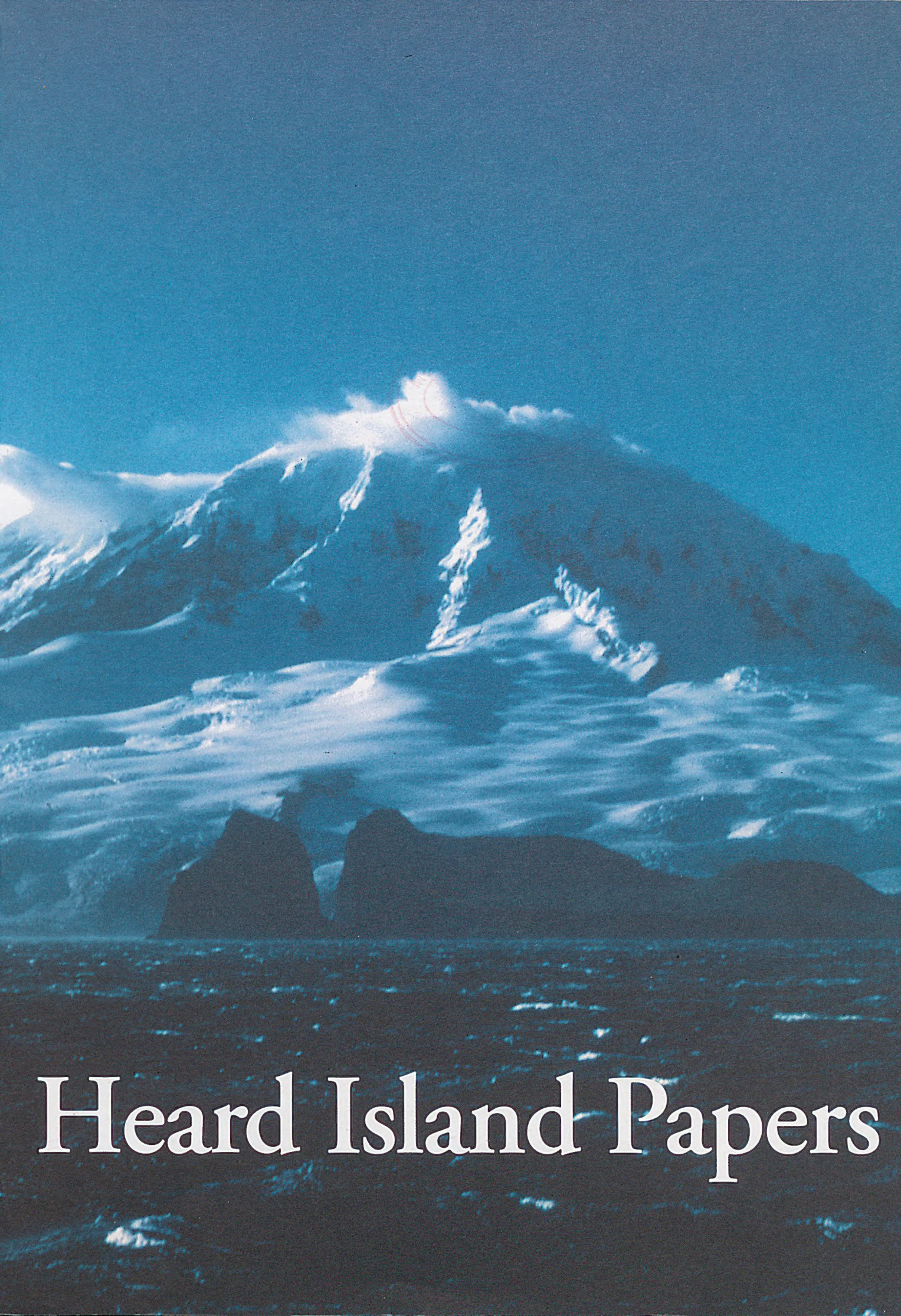

Heard Island Papers

Papers arising from the workshop
Heard Island Wilderness Reserve
held at the
Australian Antarctic Division
Kingston, Tasmania
29 June to 1 July 1998

Royal Society of Tasmania
in conjunction with the
Australian Antarctic Division, an agency of the Department of Environment and Heritage.

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PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA
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Big Ben, Heard Island, 1971 photograph by A.J. Graft
Australian Antarctic Division

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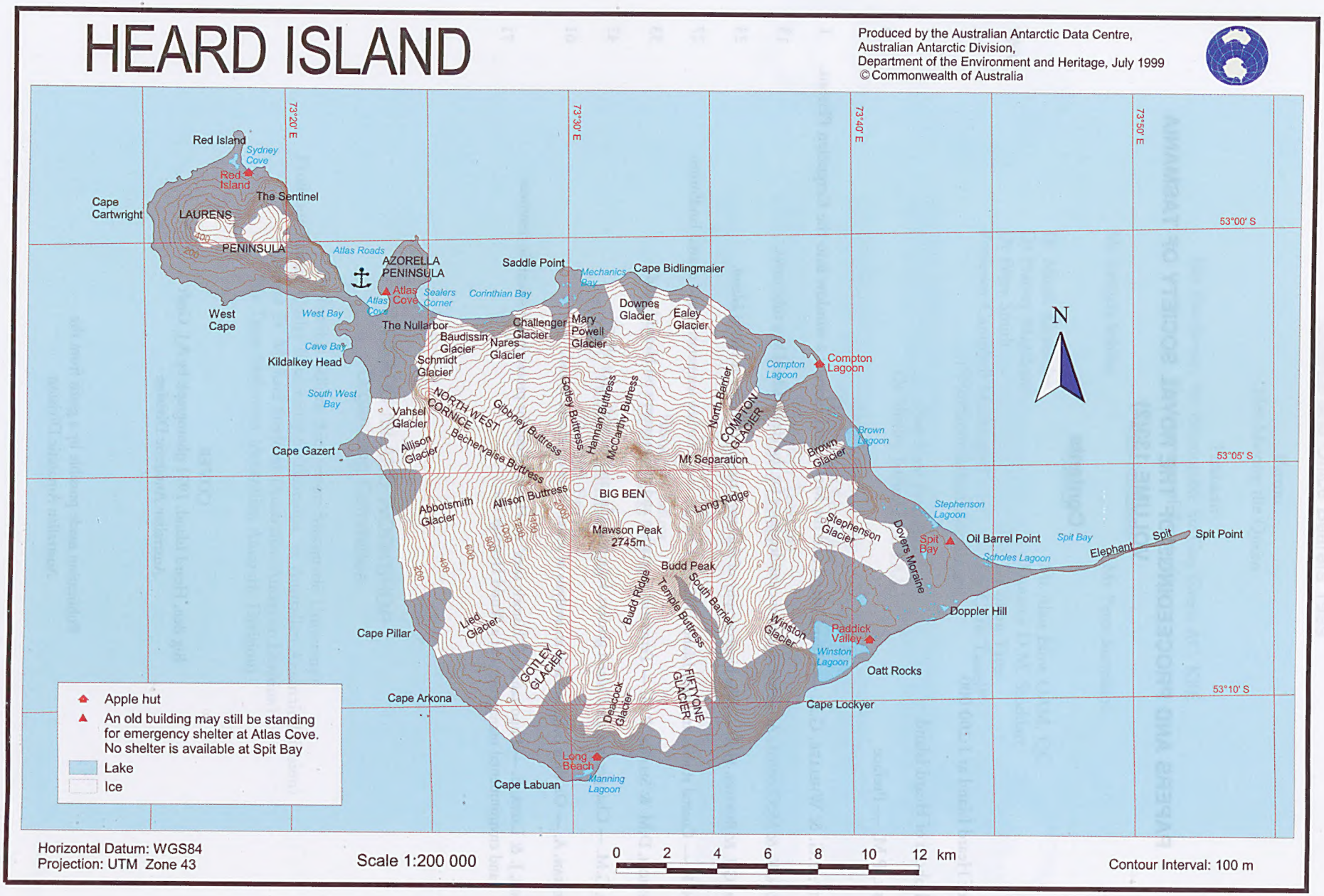
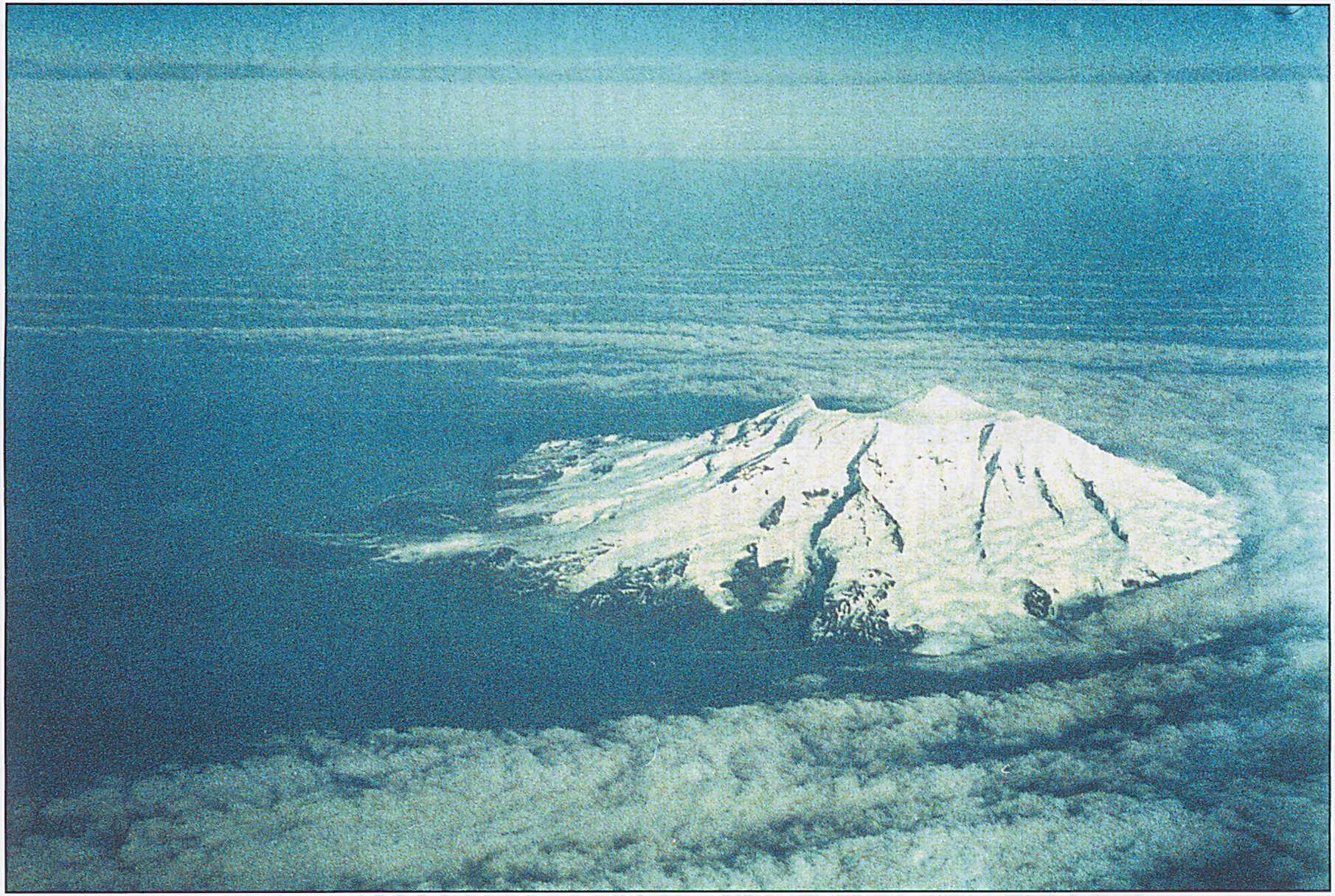


Map of Heard Island.



Aerial photograph of Heard Island — taken from the northeast. Photo courtesy of Captain Peter Schlossberger, QANTAS. Australian Antarctic Division.
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PREFACE

NATURAL SCIENCE AND CULTURAL HERITAGE RESEARCH IN THE HEARD ISLAND WILDERNESS RESERVE

Since its first sighting around 1833, remote, cloud-shrouded, glaciated Heard Island and its vicinity have attracted interest: from sealers, from archaeologists, from historians, from scientists, from the fishing industry, from tourists.

Heard and McDonald Islands in the Southern Ocean, distant from present continents, are of scientific and historical interest for myriad reasons. How and when were these isolated islands discovered? What is the geological origin of the islands? How old are they? What are the present environmental conditions on the islands? What were environmental conditions in the past? Are environmental conditions changing? What organisms inhabit the islands? Where are they found on the islands? How did the organisms get there? How do the islands interact with the surrounding ocean, with the surrounding atmosphere, with other parts of the world? How have humans influenced the islands, their biota, the surrounding ocean? What will the islands, their biota, the surrounding oceans be like in the future?

Heard and McDonald Islands are some 4850 km southeast of southern Africa, 4350 km southwest of Western Australia, 1650 km north of Antarctica, and 466 km southeast of Iles Kerguelen. Heard Island (53°06'S, 73°32'E) is dominated by Big Ben, a 2750 m active volcano whose slopes are heavily glaciated. McDonald Island (53°03'S, 72°35'E) is also volcanically active. Their climates are cool, moist, windy and heavily influenced by the vast ocean that surrounds them. Close to but south of the Antarctic Polar Front, the islands are in a part of the world whose climate appears to be changing quite rapidly. Their native terrestrial floras and faunas include few species and none at present known to have been introduced by humans. In a part of the world that is predominantly ocean, these small islands annually accommodate thousands of seals, penguins and other sea birds congregating ashore to breed. Seal populations were exploited on Heard Island for about 30 years from 1855. Fish populations are at present exploited, legally and illegally, in the ocean around Heard Island.

The Heard Island Wilderness Reserve includes Heard and McDonald Islands, nearby small islands and some surrounding ocean. It was inscribed on the World Heritage List in 1997. Scientific studies, begun with Drygalski's visit in 1902, have been conducted episodically as access was available. There is enormous interest in and scope for further scientific research on this fascinating and beautiful part of the world, for which Australia has prime responsibility.

The articles assembled here arise from a workshop held at the Australian Antarctic Division, Kingston, Tasmania, 29 June–1 July 1998, reviewing past research and planning future research in the vicinity of Heard Island. This is the first published volume devoted to articles concerning research in the Heard Island Wilderness Reserve. Its publication has been financially supported by the Australian Antarctic Division. Abstracts of all talks presented at the workshop have been published as *ANARE Research Note* 101 (Selkirk 1998).

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Chair, Workshop Organising Committee

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D.M. STODDART
Members, Workshop Organising Committee

REFERENCE

SELKIRK, P.M. (Ed.), 1998: Heard Island Wilderness Reserve: reports on natural science and cultural heritage research. *ANARE Res. Notes* 101: 1–40.

HEARD ISLAND AND THE McDONALD ISLANDS: A WINDOW INTO THE KERGUELEN PLATEAU

by Patrick G. Quilty and Graeme Wheller

(with four text-figures)

QUILTY, P.G. & WHELLER, G.E., 2000 (30:vi): Heard Island and the McDonald Islands: a window into the Kerguelen Plateau. *In* Banks, M.R. & Brown, M.J. (Eds): *HEARD ISLAND PAPERS. Pap. Proc. R. Soc. Tasm.* 133(2): 1–12. ISSN 0080–4703. School of Earth Sciences, University of Tasmania, GPO Box 252-79, Hobart, Tasmania, Australia 7001 (PGQ); Volcanex International Pty Ltd, Suite 4, 286 Macquarie St, South Hobart, Tasmania, Australia 7004 (GW).

The modern phase of volcanism on Heard Island probably is younger than one million years and is responsible for building Big Ben, the bulk of the island. The nearby McDonald Islands are less than 100 000 years old and are volcanically active. Big Ben sits on the Drygalski Formation, a Late Miocene–Early Pliocene volcanic/marine sediment with glacial influence, which occurs as a generally flat-lying, cliff-forming unit over most of Heard Island. The "basement" of Palaeogene limestone crops out mainly on Laurens Peninsula but also sporadically beneath Big Ben and occurs as clasts in volcanics. Historical eruptions of Heard Island, most recently from 1985 to at least 1992 and probably later, have occurred from Mawson Peak, the summit cone built upon Big Ben, but young lavas and ash cones are widespread around the island. Recent volcanic activity is summarised.

Heard Island and the McDonald Islands, with the Kerguelen Islands, are exposed parts of the Kerguelen Plateau, possibly the largest submarine plateau on earth, and provide geochemical and isotopic insights into the formation of oceanic plateaux, mantle plume development and the separation of Australia, India and Africa from Antarctica. The Plateau has a complex history that commenced with subaerial basaltic volcanism at 115 Ma, about 10 million years after India and Antarctica separated. It sank below sea level in the mid-Cretaceous, and subsided to its present setting as Broken Ridge and Kerguelen Plateau separated at 43 Ma when the Southeast Indian Ridge came between Australia and Antarctica. It is likely that, during its entire existence, some part of the plateau has been volcanically active, yielding a long-term geochemical record of large-scale crust-mantle evolution.

Key Words: Heard Island, McDonald Islands, Kerguelen Plateau, volcanism, volcanic activity, Big Ben, Laurens Peninsula, plume systems

INTRODUCTION

The Australian Territory of Heard Island and the McDonald Islands, centred on Heard Island at 53°06'S; 73°32'E, is one of the most isolated regions on Earth, lying in the central-southern Indian Ocean. Its closest neighbour is the French Kerguelen Islands, approximately 466 km to the northwest. The Territory hosts Australia's highest mountain (Big Ben – 2750 m) and, with the Kerguelen Islands, is the only exposed part of the Kerguelen Plateau (fig. 1), possibly the largest submarine plateau on Earth. Volcanic activity has been a feature of the region over approximately 115 million years, and Big Ben, the current mildly active volcano on Heard Island, has a history of perhaps less than one million years (Clarke *et al.* 1983). The McDonald Islands are low basaltic islands about 54 km west of Heard Island. The area was accepted in 1997 for inscription on the World Heritage List based on its geologically unique features.

This paper summarises the known geological evolution and significance of Heard Island and the McDonald Islands as a background to other studies on the biology, environmental value, and management requirements for the region.

PREVIOUS STUDIES

It is uncertain who first saw Heard Island. It was seen and recorded by Peter Kemp from *Magnet* in November 1833 and by the whaler Thomas Long in 1849. John Heard and his wife Fidelia, sighted the island in November 1853. Captain McDonald, early in 1854, discovered the islands now bearing his name. There were other sightings in 1854 and 1855. Erasmus Darwin Rogers of *Corinthian* made the

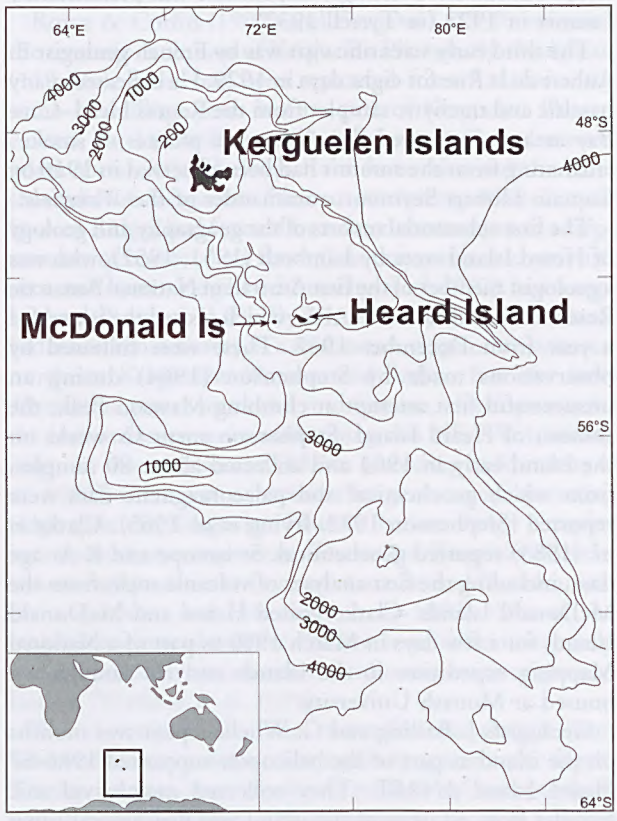

FIG. 1 — Kerguelen Plateau and its main geomorphic features.

first landing in March 1855. He returned soon after and began sealing operations which flourished until 1888.

The British did not name the island for Heard but the name was popular (under various spellings) with the sealing community and it became respectable by usage. Although originally claimed for Britain, it was transferred to Australia by "exchange of notes" on 19 December 1950 and Australia formally assumed responsibility in 1953.

The pioneering accounts of the geology of Heard Island were described by Tyrell (1937) following Sir Douglas Mawson's 1929–31 British–Australian–New Zealand Antarctic Research Expedition (BANZARE) (Mawson 1932). Tyrell described in detail the petrology of 35 samples collected by BANZARE in November 1929 and recounted three earlier scientific visits to the island. The first was on 5 February 1873 by the British *Challenger* expedition. The reports of this expedition published in 1885 included brief mentions of the volcanic rocks in the Atlas Cove area. In 1889, Renard described several basaltic rock types collected by the *Challenger* Expedition as having varying amounts of plagioclase, augite and olivine (in Tyrrell 1937).

The second visit was by the 1901-3 German *Gauss* Expedition for seven hours on 3 February 1902. A geologist of the expedition, E. Philippi (1908), gave a geological description of the Rogers Head area including the observation of *Globigerina* limestone clasts among the material ejected from some young ash cones (in Tyrrell 1937). A petrological study of Philippi's samples by Reinisch (1908, in Tyrrell 1937), incorporating several chemical analyses, revealed various basaltic rock types, including limburgites, as well as trachytes. A further analysis of a sample from the *Challenger* Expedition was presented by Lacroix in 1923 (in Tyrrell 1937).

The third early scientific visit was by French geologist E. Aubert de la Rue for eight days in 1929. He collected many basaltic and trachytic samples from the Rogers Head–Cave Bay area and reported that "immense plumes of smoke" emanating from the summit had been observed in 1910 by Captain Hobart Seymour, commander of the *Wakefield.*

The first substantial reports of the geography and geology of Heard Island were by Lambeth (1951, 1952), who was a geologist member of the first Australian National Antarctic Research Expedition (ANARE) which visited the island for a year from December 1947. These were followed by observations made by Stephenson (1964) during an unsuccessful first attempt at climbing Mawson Peak, the summit of Heard Island. Stephenson spent six weeks on the island early in 1963 and collected about 80 samples, from which geochemical and palaeomagnetic data were reported (Stephenson 1972, Irving *et al.* 1965). Clarke *et al.* (1983) reported geochemical, Sr isotope and K-Ar age data, including the first analyses of volcanic rocks from the McDonald Islands. Clarke visited Heard and McDonald Islands for a few days in March 1980 as part of a National Mapping expedition to the islands and his samples are housed at Monash University.

Geologists J. Barling and G. Wheller spent two months on the island as part of the helicopter-supported 1986-87 Heard Island ANARE. They collected mainly volcanic samples from all parts of the island and flew several times over Mawson Peak, including one landing, to observe summit crater activity. Their samples are housed at Monash University and the University of Tasmania. The major isotopic and petrological results of this visit were reported by Barling *et al.* (1988), Barling & Goldstein (1990), Barling *et al.* (1994) and Hilton *et al.* (1995). Some samples used in these studies, in addition to those obtained by Stephenson and Lambeth, were obtained by the Blunt-Vining Expedition which successfully climbed Mawson Peak in 1983 (Barling 1990a,b).

DESCRIPTION

Heard Island (fig. 2) is 43 km long from Laurens Peninsula in the northwest to the end of Elephant Spit in the southeast. The main body of the island is central, approximately circular and slightly less than 20 km in diameter. This marks the base of the main feature of the island — the historically mildly active volcano of Big Ben with Mawson Peak (2750 m) at its centre. Laurens Peninsula is also roughly circular, about 6 km in diameter and has another distinct volcano, Mt Dixon (706 m), at its summit, 19 km from Mawson Peak. Mt Dixon appears to be a very fresh volcano which formed within the last 10 000 years but has not been observed active. Radial lava flows are very clear and two flows in particular are unvegetated and probably less than a few hundred years old. Small ash cones and related lava flows also occur in places close to the coast around the island. Elephant Spit is a sand spit some 10–12 km long, extending east from the island and composed of glacial and fluvial debris carried east by current activity. It is sometimes cut by the sea and varies in form.

The basement of Heard Island, visible best around the southern margin of Laurens Peninsula, consists of weakly to strongly indurated Palaeogene limestone, folded at some stage and now inclined at a variety of dips. The surface was planed before the deposition about 4–10 million years ago of a blocky horizontal rock unit — the Drygalski Formation — which contains evidence of shallow marine conditions and volcanic and glacial influences. It forms a solid unit of roughly uniform thickness. It, in turn, was planed before the Big Ben volcano was formed, over the last one million years.

The island is heavily glaciated with glaciers radiating from Mawson Peak and on Laurens Peninsula. The age of the oldest ice on the island is not known but estimated to be approximately 100 years. Glaciers have been in marked and documented retreat (Lambeth 1951, Ruddell & Allison 1997, Budd 2000) since the occupation of the island in 1947.

Heard Island is marked by unusually well-developed buttresses radiating from the main peak and separating individual glacial valleys. They probably owe their origin to the effects of erosion by radial glaciers, ordinary avalanches in fragmental volcanic sediments, and major debris avalanches. They are lacking in the southwestern sector.

The history of the island and its volcanoes has not been fully documented. Mawson Peak is a small, classical volcanic cone sitting as a distinct entity on a plateau on the top of Big Ben, with a southwestern face reaching the sea with an uninterrupted uniform slope. To its north, east and southeast, it is surrounded by a scarp which marks the position of a debris avalanche amphitheatre. Formidable ice-cliffs surround the plateau on its northern and eastern sides. The upper part of Big Ben appears to have slumped to the southwest and the current, considerably younger, small volcano has rebuilt inside the resulting landslide scar.

About 45 km west of Laurens Peninsula lies McDonald Island which appears to have been visited only twice by humans and, thus, has value because it appears pristine.

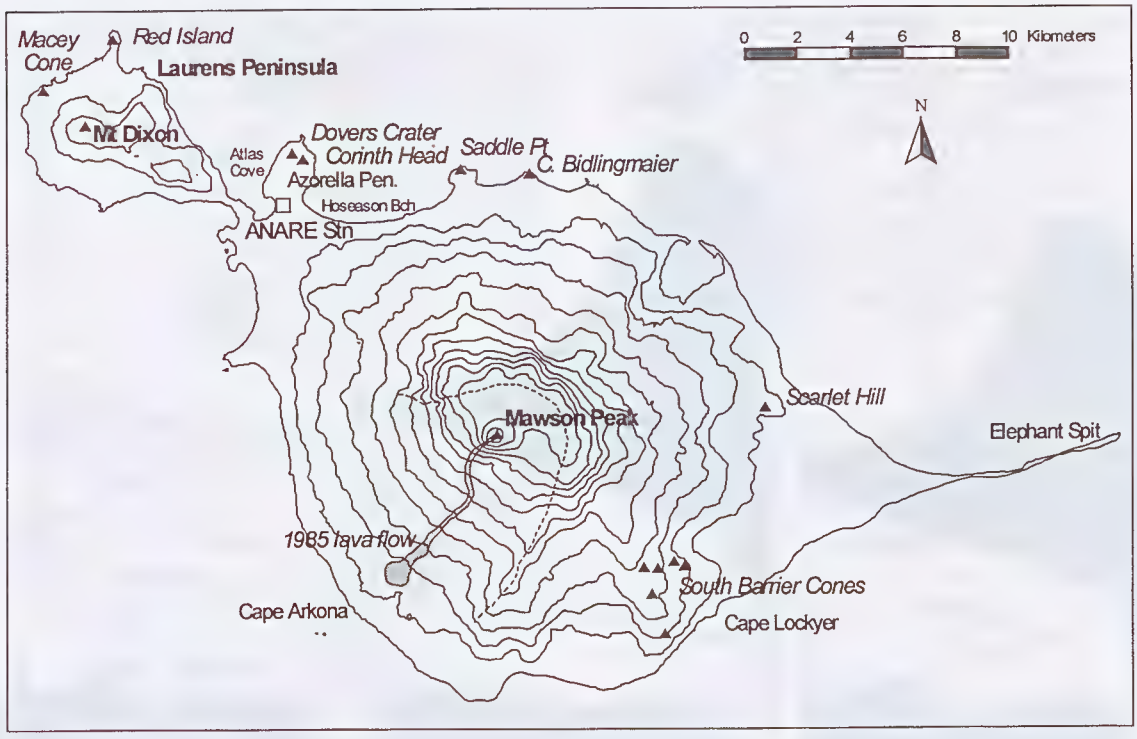

FIG. 2 — Locations on Heard Island mentioned in the text.

Until recently, it was thought to have been evolved over the last 100 000 years (Clarke *et al.* 1983) with the youngest known lavas of about 35 000 years. The island is composed of a phonolitic lava, which is very different from the basanite-alkali basalt-trachyte series which characterises Heard Island and includes feldspathoids. In 1992, pumice in large quantities washed up on Heard Island but is identical in composition to the rocks composing McDonald Island (J. Sheraton, pers. comm., 10 June 1993; Collerson *et al.* 1998). Similar pumice from the head of Atlas Cove was analysed by Tyrrell (1937, Table X, sample 10). The presence of fresh pumice was initially taken as evidence of a submarine eruption in the area (Quilty 1995); however, in March and April 1997, active steam plumes were seen at the northern end of McDonald Island, suggesting that a subaerial eruption may have occurred in this area.

Interestingly, fresh pumice on Heard Island also occurs on higher elevations (Stephenson 1964) and in a primary bed a metre thick under thin moraine at Spit Bay. These pumices are trachytic and essentially identical in composition to the trachytic lavas around Laurens Peninsula (Stephenson 1964, Barling *et al.* 1994, Wheller pers. obs.). Their source is unknown although it is probably in the high parts of the Laurens Peninsula where the trachytic lavas are concentrated.

Shag Island and two other small islets lie about 9 km north of Heard Island and are other emergent, though unstudied, outcrops.

ORIGIN AND EVOLUTION OF KERGUELEN PLATEAU

The history of Kerguelen Plateau (fig. 3) was investigated by Ocean Drilling Program (ODP) Legs 119 and 120 in 1988, and Leg 183 in 1999. The Kerguelen Islands are more complex than Heard Island, because of their longer history (fig. 4) and great differentiation of lava types (Nougier & Thomson 1990).

Royer & Coffin (1992) and Fitzgerald (1999) reviewed the tectonic evolution of Kerguelen Plateau. By the Aptian (119 Ma), India had been separated from Antarctica for some 13 million years but no part of Kerguelen Plateau existed. By 110 million years (Albian), India had moved north about 10° of latitude from Antarctica and the basic structure of Kerguelen Plateau (including what is now Broken Ridge) had formed by subaerial extrusion of a large number of basaltic lava flows ("excessive volcanic activity" on a mid-ocean ridge — Munschy *et al.* 1992) in a Large Igneous Province (LIP). By 84 million years (Santonian), India had moved away as a mid-ocean ridge came between northern Kerguelen Plateau and India. For the next 40 million years, until the mid-Eocene, development in the Indian Ocean was mainly along this NE–SW trending ridge. In the mid-Eocene (43 Ma according to Munschy *et al.* 1992), there was a marked change as a new spreading ridge split the Kerguelen Plateau/Broken Ridge complex into its modern components. Thereafter, Kerguelen Plateau was an independent entity and characterised by volcanism at its northern end (Munschy *et al.* 1992). One of the major questions about the Plateau is whether it is purely oceanic or has some continental influence in its origin and history (Watkins *et al.* 1974).

The tectonic history also controlled the change from subaerial to marine deposition and subsequent water depth. The Aptian lavas were weathered to form red soils in which grew forests of conifers (*Podocarpoxylon*) that were affected by forest fires, possibly initiated by volcanism (Francis & Coffin 1992). Palynology (Mohr & Gee 1992) indicates abundant terrestrial vegetation until the Late Cenomanian (92 Ma). Much of Kerguelen Plateau sank below sea level near the Turonian/Cenomanian transition and underwent

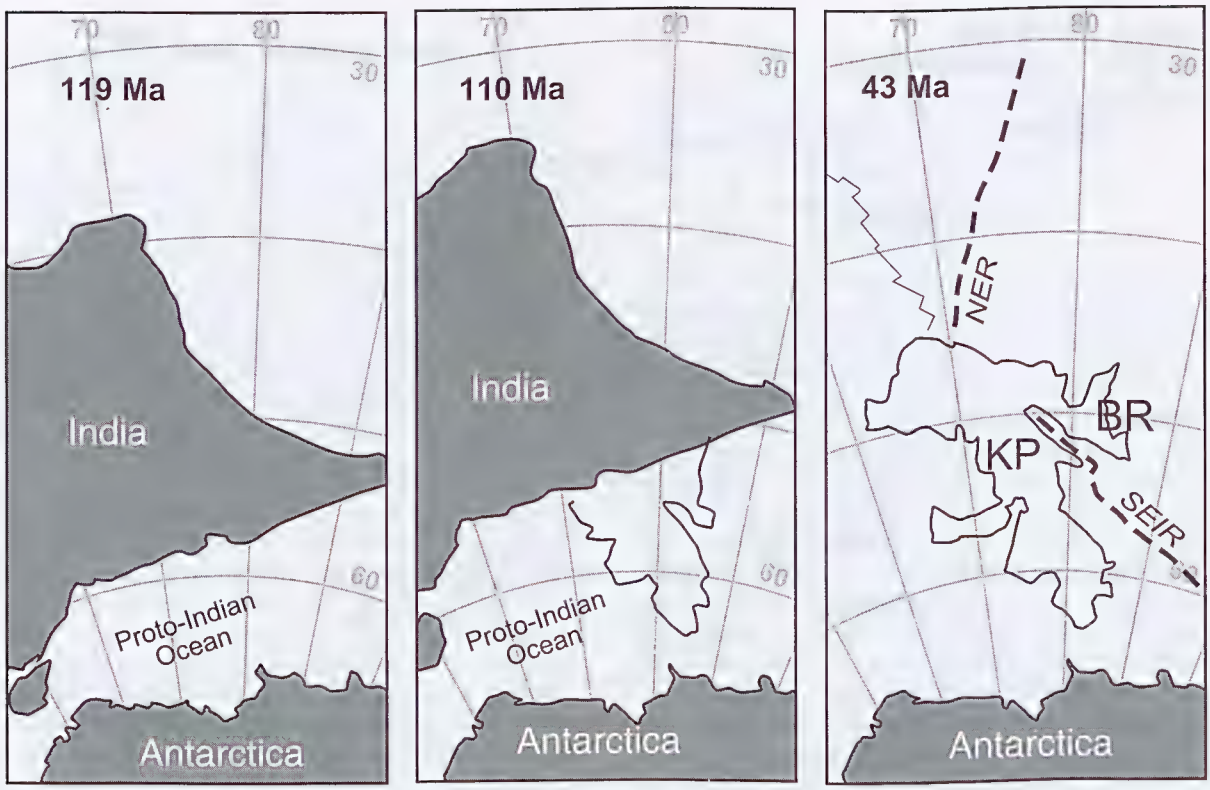

FIG. 3 — The evolution of Heard Island and of Kerguelen Plateau at 119, 110 and 43 Ma (after Royer & Coffin 1992). NER – Ninetyeast Ridge; SEIR – Southeast Indian Ridge.; KP – Kerguelen Plateau; BR – Broken Ridge.

deposition of carbonate sediments dominated by the remains of various microfossils, especially foraminifera and calcareous nannoplankton.

Throughout the history of the Plateau (fig. 4), over 115 million years, it is likely that vegetated islands have stood above sea level. Volcanism probably was active through all this time somewhere on the Plateau.

SUCCESSION ON HEARD ISLAND

The most prominent volcano on Heard Island is one million years old or less (Clarke *et al.* 1983) and sits on a complex basement. The history is poorly known and no proper geological map of the island exists.

Two broad intervals of island history are apparent. The first involves the dominantly carbonate sediments that constitute the dipping basement. The latter consists of three volcanic phases.

Palaeogene "Basement" of Heard Island

In places near sea level on both sides of the eastern Laurens Peninsula, in small areas around Big Ben behind Hoseason Beach, and on the eastern side of Azorella Peninsula near Corinth Head, the Laurens Peninsula Limestone (Lambeth 1952) crops out unconformably beneath the Drygalski Formation. The limestone consists mainly of thinly bedded, generally light-coloured, nanno oozes of unknown thickness which contain planktonic foraminifera and calcareous nannofossils, together with less common argillaceous limestone containing miospores and dinoflagellates. The disposition of clasts suggests that the limestone is everywhere close to sea level. It forms the "basement" of the island and is part of the carbonate succession studied on Kerguelen Plateau by the activities of ODP Legs 119, 120 and 183.

Ages of "lower Tertiary" (Glaessner in Lambeth 1952), and Late Paleocene, Eocene and Oligocene (Quilty *et al.* 1983) have been recorded but can be refined if fresh, less lithified material can be obtained. Material studied to date has been highly lithified with stylolites common, suggesting significant depth of burial or tectonic pressure. Lambeth (1952) refered to "thin soft tuffaceous shales" in the sequence indicating the existence of non-lithified material. Stephenson (1964) believed that the dips resulted from faulting or intrusion rather than the compression that Lambeth favoured. More information about coeval vegetation may be gained from study of darker sediments in the sequence that may contain a palynological record. The only indication of the thickness comes from ODP drilling (70 m of Palaeogene carbonate at Site 747; Schlich *et al.* 1989).

After deposition, these pelagic sediments were tilted to some 25–35° with an east–west strike, but neither cause nor the timing are documented. It may relate to separation of Kerguelen Plateau and Broken Ridge at 43 Ma (Munschy *et al.* 1992). Since it was tilted, the limestone has been planed by erosion to produce a gently south dipping surface which is about 75 m a.s.l. on southern Laurens Peninsula.

These sediments accumulated in open ocean, sometimes cool, conditions. The foraminiferal faunas contain small, thin-walled globigerinid forms and lack diversity. While cool, there is no indication of glacial conditions.

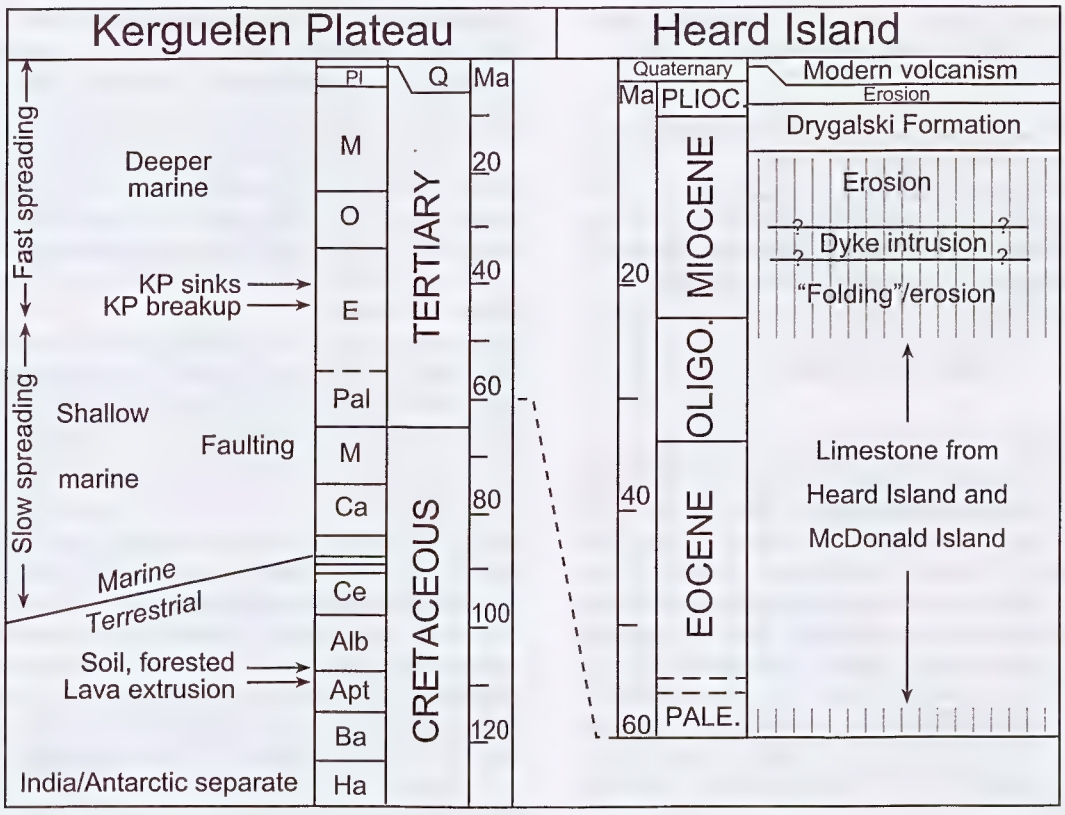

FIG. 4 — Stratigraphy and history of Kerguelen Plateau and Heard Island.

Miocene/Pliocene Volcanism

The first phase is no older than Late Miocene and is represented by intrusives into the limestone basement (Stephenson 1964, Clarke *et al.* 1983). Behind Hoseason Beach, the intrusion is about 30 m thick.

The second phase is Late Miocene–Early Pliocene and these basaltic volcanics were erupted during glaciation to form the Drygalski Formation of conglomerate/sandstone/mudstone. The Drygalski Agglomerate or Formation is one of the main rock units on Heard Island and crops out around the island as a solid, blocky, cliff-forming formation. Called the Drygalski Agglomerates by Lambeth (1952) and the Drygalski Formation by Clarke *et al.* (1983), it consists of volcanolithic breccia, hyaloclastite, pillow lava and tillite. It is generally horizontal, but in places basaltic sills and dykes and dioritic stocks, cause local deformation. The sequence is exposed in cliffs up to 200 m high along the northern and eastern coasts, and beneath the South Barrier on the south coast. Its base overlies the Palaeogene limestone with a 35° unconformity surface (Lambeth 1952), and the top forms a flat upper erosional surface.

The Drygalski Formation needs detailed study to define its age, origin, palaeoenvironment and structure. Stephenson (1964) made comprehensive observations which indicate it is up to 300 m thick (Lambeth 1952 suggested 350 m), but thickness varies. Massive and pillow lavas indicate submarine volcanism and it may be glacial in part, based on the presence of striated boulders. Fleming (1957) described the bivalve *Chlamys heardensis* from this unit and Quilty *et al.* (1983) recorded a few fossils from near Cape Lockyer.

During deposition of the Drygalski Formation, the geography of the region was different from the modern. Stephenson (1964) believed some of the Drygalski Formation came from nearby emergent land to the north.

Quaternary Volcanism on Heard Island

The final phase of volcanism produced the two landforms that dominate modern Heard Island, Big Ben and the Laurens Peninsula area. The products are dominantly lavas with little ash apart from that forming small satellite ash cones in various places around the coast. A primary trachytic pumice deposit about a metre thick occurs near Spit Bay, overlain by a thin moraine deposit, and Stephenson (1964) reported abundant angular pumice clasts on Mt Drygalski and Mt Aubert de la Rue. Clarke *et al.* (1983) regarded the history of this phase of volcanism as being unlikely to extend beyond 1 Ma ago, based on K-Ar age dating of lavas and general morphology.

Overall, the lavas are mainly highly porphyritic basanites (limburgites and ankaramites), alkali basalts and trachybasalts. They contain abundant and large phenocrysts of clinopyroxene, typically strongly zoned, and olivine with lesser amounts of plagioclase, titanian magnetite and ilmenite phenocrysts in glassy or holocrystalline groundmasses. Sparsely porphyritic trachytic rocks occur mainly on the Laurens Peninsula area, forming the major landforms of the area, including the remnant crater of Cave Bay, and underlying the younger basaltic flows erupted from Mt Dixon. Compared to the basalts, the trachytes contain kaersutite and biotite, less clinopyroxene, titanian magnetite and ilmenite, more plagioclase, and only rare olivine. The trachytic sequence appears to have been rapidly uplifted prior to the Mt Dixon basaltic volcanism, possibly as a

result of the emplacement of a shallow cryptodome which is yet to be revealed by erosion (Barling 1990a, b).

HOLOCENE VOLCANIC FEATURES

Many young volcanic features, which have not been described in detail previously, are present on Heard Island. The following observations result largely from fieldwork by Wheller during the 1986–87 Heard Island ANARE.

Big Ben Group

Mawson Peak

In January 1987, the summit of Mawson Peak contained a cylindrical crater 40–50 m across and 50–70 m deep that was not observed during two earlier successful ascents of Mawson Peak. In 1965, the first party reported seeing only a deep furrow 25 ft deep, 75 ft across and 250 ft long. The second party, in 1983, saw a rocky area from which steam was being emitted. The crater, therefore, probably formed as a result of a 1985 eruption. Between December 1986 and January 1987, during the 1986–87 Heard Island ANARE, observations from helicopter revealed that the crater contained a lava lake with a black ropey surface which periodically opened to reveal red molten lava. An Army Alpine Association climbing party which reached the summit in January 2000 reported seeing "a large vent about 10 m long with smoke billowing out continuously" (Wheller pers. comm.).

Mawson Peak sits in a semicircular plateau bounded to the north and east by a pronounced ridge rising 100–200 m above the plateau and, from each side of the plateau, the flanks of Big Ben extend almost to sea level. The smooth southwest sloping surface, 5 km wide at its top, between the flanking ridges (Allison Buttress and Holmes Ridge) is markedly distinct from the rugged topography of the other parts of the flanks of Big Ben and is suggestive of a large-scale landslide — a debris avalanche. Stephenson (1964) suggested that the summit is a caldera, indicating an origin by volcanic collapse, but an origin by slumping into the sea of a large part of Big Ben, including its original summit, seems more likely. Mawson Peak has subsequently grown by the eruption of volcanic material near the top of the slump, probably close to the site of the earlier summit. The seafloor southwest of the island has not been charted properly but is shallower than that around other parts of the island, probably reflecting the site of debris from the volcano.

The 1985 lava probably formed when magma filled the crater and spilled over through a deep notch on its southern side. It flowed down the southwest of Mawson Peak along a sigmoid path about 8 km long through the glacial ice, terminating in a narrow ice valley 70–100 m wide and 20–30 m deep about 450 m a.s.l. and 3 km from the coast. The lava flow surface is slightly spinose but generally smooth with a copper-coloured sheen. Pahoehoe and ropey patches up to a few metres across are common. "Entrail" pahoehoe also occurs in places where lava flowed over large, earlier lava blocks.

The lava is highly vesicular and coarsely porphyritic, comprising about 10% phenocrysts of olivine, clinopyroxene and rare titanian magnetite in a holocrystalline basaltic groundmass of plagioclase, clinopyroxene and ilmenite microlaths and titanian magnetite microprisms. Olivine phenocrysts are smaller but more abundant than those of clinopyroxene and are generally subhedral and unzoned, except for slight marginal zoning. A few show undulose extinction and many contain small inclusions of chromian spinel and brown glass. Clinopyroxene phenocrysts are generally subhedral, in places occur in glomerocrysts, display complex oscillatory zoning and contain inclusions of brown glass and chromian spinel. (Wheller, pers. obs.).

Azorella Peninsula

Azorella Peninsula is a low headland about 2 km wide and 3 km long to the northwest of Big Ben. It is built mainly of thin basanitic and basaltic flows, exposed in the cliffs forming the edges of the peninsula. At least the uppermost flow emanated from a 100 m high composite cone forming the southwestern shoulder of Corinth Head. This unnamed, flat-topped cone possesses a partly infilled summit crater about 30–40 m wide and there are several small subsidiary craters on its western side. Thin layers of scoria and lava are exposed in the summit crater walls.

Although moderately vegetated the uppermost lava appears young and covers most of the peninsula. It is moderately vesicular and coarsely porphyritic, comprising about 20% phenocrysts of subhedral olivine and much less abundant clinopyroxene in a hyalocrystalline groundmass containing clinopyroxene microprisms. Some larger olivine phenocrysts are partly rounded and embayed with undulose extinction. Many contain small chromian spinel inclusions. Except for its southern margin the lava extends to the edges of the peninsula where it has been truncated by the continuing marine erosion. It is bounded on its southern side by volcanolithic sandy moraine. Small lava tunnels, striking westwards, and collapsed tumuli occur in the northern part of the peninsula.

Eroded remnants of trachytic pyroclastic volcanics of ash cones on Azorella Peninsula are evidence of a period of pyroclastic volcanism which predates at least the uppermost lava flow, and may once have formed parts of the same large complex cone, almost all of which has been destroyed by glacial or marine erosion. Each remnant — Rogers Head, Corinth Head and Balanced Rock — is constructed of thin-layered, well-sorted, medium-grained, leucocratic tuff, partly comprising abundant olivine and clinopyroxene crystals, and dips at about 30° to the west and southwest, indicating that the main part of the cone lay off the present northeast margin of Azorella Peninsula. Prominent disconformities are exposed in the tuff sequences, indicating marked shifts in pyroclastic activity during deposition.

Dovers Crater is a small basaltic scoria cone in the western part of the peninsula. It is mantled by a thin-layered 0.5 m thick deposit of leucocratic olivine- and clinopyroxene-bearing tuff. The deposit contains abundant basaltic lava blocks up to about 0.3 m across. Many of these lie in deep sags in the underlying tuff, indicating that they were deposited as ejecta coevally with the tuff. Small limestone clasts are also present but less abundant than the basaltic blocks.

Saddle Point

Saddle Point consists of a small composite ash ridge about 40–50 m high and 100 m long, and associated basaltic lava flow joined to Big Ben by a small, low-lying sand plain. A large part of the ridge has been destroyed by encroaching marine erosion but a deep, well-formed summit crater about

30 m across, surrounded by lava spatter, remains at its western end. The highest point lies 107 m a.s.l.

The lava is moderately vegetated and its northern side has been truncated by marine erosion. It is moderately vesicular and coarsely porphyritic, comprising about 10% phenocrysts of olivine and much less abundant clinopyroxene in a hyalocrystalline groundmass containing clinopyroxene and plagioclase microprisms, ?titanian magnetite granules and ilmenite laths. Olivine phenocrysts vary widely in size, contain small glass and chromian spinel inclusions and are generally subhedral, with some rounded and embayed. Rare large crystals show undulose extinction and strong marginal zoning. Clinopyroxene phenocrysts are mostly euhedral and generally smaller than those of olivine. Larger crystals display mottled interior zoning and broad oscillatory-zoned rims.

Cape Bidlingmaier

Cape Bidlingmaier is also a small volcanic headland on the northern side of Big Ben. It consists of a series of basaltic lava flows, exposed in sea cliffs formed as a result of encroaching marine erosion, and a well-formed but partly eroded ash cone. The summit of the cone is 120 m a.s.l. Lava spatter and small spherical bombs are common around the summit area. An unusual feature of the cone is that its southern flank is entirely covered by a prominent moraine which just extends into the summit crater. The cone, and its associated lavas, are older than the last glacial maximum on Heard Island.

The uppermost lava flow on Cape Bidlingmaier is ropey basalt, moderately vegetated, and markedly different from the other young lavas around Big Ben. It is lightly vesicular and finely porphyritic, comprising about 5% small euhedral phenocrysts of olivine, clinopyroxene and titanian magnetite in a holocrystalline groundmass of plagioclase microlaths and clinopyroxene and titanian magnetite granules. A few larger, embayed olivine phenocrysts are also present, and both they and the euhedral olivine phenocrysts contain small chromian spinel inclusions.

Scarlet Hill

Scarlet Hill consists of a prominent red scoria cone with broad summit crater lying over a narrow, flat-topped and steep-sided rampart on the northeast flank of Big Ben. The southern side of the rampart has been eroded by glacial activity and the summit crater is open towards the south. A small tongue of lava lies on the eastern flank and another small flow extends from beneath the eastern side to the edge of the northern cliff face of the rampart and onto the scree slope below. This lava clearly formed after erosion, during a period of glaciation more intense than the present, which formed the northern side of the rampart. It is finely vesicular and coarsely porphyritic, comprising about 15% phenocrysts of olivine and clinopyroxene in a hyalocrystalline groundmass containing scattered plagioclase microlaths and clinopyroxene microprisms. Olivine and clinopyroxene phenocrysts are approximately equally abundant. Olivine phenocrysts are mostly subhedral, with some rounded and embayed, and contain small glass and ?chromian spinel inclusions. Some clinopyroxene phenocrysts are euhedral and display strong oscillatory zoning; others are rounded and embayed with internal melt zones and show complex mottled zoning.

South Barrier

The South Barrier is a major escarpment extending for 7.5 km from the eastern side of the summit ridge of Big Ben to the coast. Behind its lower part, there is a broad plateau bearing three well-formed scoria cones and at least two mappable young lavas. The remains of a fourth scoria cone lie at the southwestern corner of the plateau. Half of this prominent red cone has been destroyed by coastal erosion. While the summit of the eroded cone is missing, the three complete cones possess deep summit craters, two of which comprise two distinct sub-craters. The existence of the cones was first noted by Stephenson (1964), who observed them during an unsuccessful attempt to climb to the summit of Mawson Peak.

The youngest lavas lie on the western and eastern sides of the plateau. The eastern lava flowed southeast, at least as far as the southern and eastern margins of the plateau where it has been truncated by erosion, and is virtually unvegetated; however, the absence of vegetation probably results from very harsh climate more than the recent age of the flow, which is dull grey in colour, blocky and does not appear to be very young although petrographically very fresh. It is moderately vesicular and coarsely porphyritic, comprising about 5% medium-sized phenocrysts of olivine and clinopyroxene in a fine-grained holocrystalline groundmass of plagioclase microlaths and clinopyroxene and titanian magnetite granules. The groundmass has a trachytic texture in places. Olivine and clinopyroxene phenocrysts are approximately equal in abundance and generally subhedral. Some olivine phenocrysts are rounded and embayed and contain small glass and chromian spinel inclusions. Clinopyroxene phenocrysts are slightly more rounded than those of olivine and display mottled interior zoning together with thin oscillatory-zoned rims.

The western lava flowed south from a small vent between two cones, at least as far as the southern margin of the plateau, where it has been truncated by erosion. Although also coarsely porphyritic, it is distinct from the eastern lava, with phenocrysts of olivine, clinopyroxene and less abundant titanian magnetite and plagioclase in a holocrystalline basaltic groundmass of plagioclase microlaths and clinopyroxene and titanian magnetite granules. Olivine and clinopyroxene phenocrysts are approximately equal in abundance. Olivine phenocrysts are mostly anhedral; some show thin marginal zoning and many contain small glass and chromian spinel inclusions. Most clinopyroxene phenocrysts are subhedral, although some are partly rounded and deeply embayed. Larger crystals display mottled interior zoning and thin oscillatory-zoned rims. Plagioclase phenocrysts occur as complex laths showing oscillatory zoning.

The young plateau lavas are bounded in many places by flow fronts 1–2 m high but are truncated sharply elsewhere by rapidly eroding western, southern and eastern margins of the plateau. Moreover, in the centre of the plateau, two of the lavas have north-trending erosional boundaries which face each other across a broad, shallow valley floored by smoothed older lavas overlain in places by volcanolithic moraine. Evidently, a glacier once flowed across the central part of the plateau and truncated the pre-existing lava flows at its margins.

The funnel-shaped pattern formed by moraine ridges on the northeastern side of the plateau, at the head of the postulated glacial valley, also suggests that a glacier once flowed across the plateau and crossed its southern margin on the western side of Cape Lockyer.

The presence of other moraine ridges in the northwestern part of the plateau also indicates the occurrence of widespread earlier glaciation on the plateau. However, in this area, one of the scoria cones lies over part of one moraine ridge and a young lava flowed down the valley between two ridges. Volcanism therefore postdates glaciation in this part of the plateau.

Lavett Bluff–Cape Labuan

Basaltic lava of young appearance occurs near sea level on the eastern side of Lavett Bluff, on the south coast, and a black-red basaltic scoria sequence forms the bluff itself a few hundred metres higher. However, no obvious vent has yet been found in the area. The sources of similarly young lavas in the Cape Labuan area are also unknown.

Laurens Peninsula Group

Mt Dixon

Laurens Peninsula is about 8.5 km long x 6 km wide, joined to Big Ben by a high-standing narrow isthmus. At its western end the smaller volcano, Mt Dixon, occurs as a relatively small dome, with its summit about 706 m a.s.l. and entirely covered by permanent ice. Many young, ropey, blocky and spinose basaltic lavas around its south and west were erupted from small vents low on the flanks. A prominent line of shallow craters occurs on the western flank, including a substantial pit crater and four hornitos at its western end near Cape Cartwright. One of the hornitos is still well-formed, about 2 m high, 4 m in diameter and hollow.

The basaltic lavas are underlain on the western and northern sides of Mt Dixon by trachytic lavas. In places, around the coast, particularly behind Macey Cone, the trachytic flows have been truncated by marine erosion, resulting in the formation of low cliffs and terraces over, or against, which some of the basaltic lavas lie. This erosion may have occurred during the most recent sea-level maximum in the southern oceans at about 6000 years BP (Berkman 1992).

Two black lavas of very young appearance lie on the northern and southern flanks of Mt Dixon. They are essentially unvegetated apart from lichen developing on their margins. The northern lava is by far the larger in area and its source appears to be high on the northern side of Mt Dixon. It extends to, and is truncated by, the coastline southwest of Red Island. The southern lava appears to have flowed from a separate vent on the upper southeastern flank of Mt Dixon. It formed two lobes, one of which is truncated by the present coastline. The presence of these youthful lavas, perhaps less than 200 years old, indicates that Mt Dixon is likely to erupt again in the future. The appearance of most of the other Mt Dixon lavas suggest they may only be a few thousand years old. Some flows on the southern flank are littered with large erratic boulders of trachyte and coarse-grained diorite, suggesting that they are older than the most recent glacial maximum. The most densely vegetated flow occurs east of West Cape. It has a mappable flow front and appears to have been erupted from four or five small vents evenly spaced along the base of an ash ridge about 500 m long. Ejecta among the ash and vesicular lava bombs include rare chert and limestone clasts, similar to the Laurens Peninsula Limestone exposed about 3 km to the east, and altered olivine-pyroxene xenoliths.

Red Island

Red Island is a small ash cone and associated lava field joined to the northwestern tip of Laurens Peninsula by a narrow sandy isthmus with a central lagoon. Only the eastern half of the cone is preserved, the western side having been eroded away by the sea. The western face, the exposed interior of the cone, shows a 2 m thick trachytic lava concordantly overlain by about 30 m of ash and breccia. On the northern side of the cone lies the topmost of about 5–6 lava flows that are exposed in section in the sea-cliffs. An older, more vegetated flow lies to the east and south.

Elephant Head–Macey Cone–Cape Cartwright

The westernmost sector of the Laurens Peninsula coastline contains the substantial ash cones, Elephant Head and Macey Cone, and a series of small lavas and ash cones near Cape Cartwright. Macey Cone is the most prominent feature, comprising an almost complete ash cone 124 m high with a well-formed, deep summit crater. An associated lava flow emanates from a vent on the southwestern foot of the cone. Immediately along the coast to the northeast of Macey Cone is Elephant Head, which is the remnant of a substantial ash cone apparently similar in size to Macey Cone. It is now largely eroded by the sea but displays a prominent discordant breccia body (the "elephant's trunk") which is interpreted to be a remnant of the crater in-fill breccia.

About a kilometre south around Cape Cartwright are several ash cones and small lava flows. The source of a small ropey lava on the edge of the coast midway between Macey Cone and Cape Cartwright appears to have been seawards of the current coastline, indicating that other young vents in the area may have been eroded away by the sea.

Four Bays Area

Remnants of vents significantly older than the coast ash cones occur in the area of the isthmus joining Laurens Peninsula to Big Ben, bounded by Atlas Cove, Corinthian Bay, West Bay and Southwest Bay. The largest feature is a circular, columnar-jointed trachytic dome at Cave Bay. It is about 1.5 km in diameter and its western side has been breached by the sea, resulting in preferential erosion of its centre, such that its northern and southern sides form two ridges which enclose Cave Bay. The top part of the northern ridge, Mt Andree, is covered by a thick layer of red-black basaltic ash, scoria and lava blocks and bombs, suggesting the presence of a small basaltic vent of young age. Similar material occurs near the summit of Mt Drygalski but without any obvious vent. Mt Aubert de la Rue also appears to be the remnant of a relatively old trachytic vent.

HISTORICAL ERUPTIONS OF HEARD ISLAND

Flames and fumes on Big Ben were first observed on 2 June 1881 (Aubert de la Rue 1953). On 25 March 1910 a party on the South African sealer *Mangaro* landed and saw "immense clouds of smoke" issuing from the summit (Anonymous 1910, Neumann van Padang, 1963). Similar observations were made offshore from *Wakefield* in April 1910 (Aubert de la Rue 1953, Neumann van Padang 1963). Although there was sealing on the island from about 1853 to 1875 and scientific expeditions called at Heard Island in February 1873 (*Challenger* Expedition — Renard 1889),

February 1902 (*Gauss* Expedition), January 1929 (Aubert de la Rue 1929) and November 1929 (BANZARE 1929–1931 — Mawson 1932), no other volcanic activity is known between the island's first sighting in 1833 and the establishment of a continuously occupied ANARE station in December 1947 (Tyrrell 1937, Roberts 1950).

Occupation of the research station may have coincided with a major eruptive phase. Station reports (September 1948–December 1954) described frequent emission of steam and smoke from Big Ben (Neumann van Padang 1963). Continuous reporting of activity was impossible because low cloud renders the summit rarely visible from sea level, even in summer. Between January 1950 and February 1952, up to three distinct red glows were observed around the summit, reportedly from at least two distinct vents.

Similar red glows were observed from *Marion Dufresne* during the nights of 14 January 1985 (Williams & Duhamel 1986), 1 and 2 October 1985 from *Nella Dan*, and 4 November 1985 (from near the ANARE station — Burton & Williams 1986). The *Marion Dufresne* observations included the sighting of a 200–500 m long flow which spilled over the summit rim at several places. Observations from *Nella Dan* indicated two distinct glows. A substantial bluish plume issuing from the summit was also observed during the day following the *Marion Dufresne* sighting of red glows, on the same day as the ANARE station observation of red glows and later on 17 November from Southwest Bay.

A plume from Heard Island was also observed between 7 October and 3 November by space shuttle astronauts (*Bulletin of the Scientific Alert Network* 1985). However, while these observations extend from January to November in 1985, the activity may not have been continuous during this period, as no plume was observed on 25 October and 3 November 1985, although the summit region was fully visible. Several periods of increased seismicity around Heard Island were detected on Kerguelen Island, 466 km to the northwest, between January and June 1985 (Williams & Duhamel 1986).

Helicopter flights over Mawson Peak, and a brief landing on its summit, during 1986/87 enabled clear observations of the summit crater and of the 1985 lava flow, including the path of the lava. Despite perfect visibility, no possible vent for the 1950–52 and 1985 eruptive phases other than the summit crater of Mawson Peak was observed, so reports of two or more red glows around the summit must be attributed to magma ponded in the crater and to lava flowing down the flank of Mawson Peak. The latest observed volcanic activity on Heard Island, 7 December 1986–4 January 1987, consisted of a lava lake at the base of the summit crater, and intermittent and gentle emission of small amounts of bluish smoke and steam. A small explosive emission, resulting in a dark brown stain over the ice surrounding the crater, occurred on 3 January 1987.

A December 18 1992 earthquake (M = c.4) may have been related to eruption of basalt on Big Ben, rather than to the "McDonald Island pumice source". It is clear that there had been a significant eruption of basalt from the peak on Big Ben forming a flow to the southwest over a horizontal distance of 4.5 km and vertical elevation of some 1200 m. The flow was approximately 50–100 m wide and divided into two lobes at an elevation of about 1500 m, approximately 0.5 km from its terminus. Steam was still evident at the terminus indicating that the flow was not "very old". A message from R. Ledingham, geologist on a tourist ship in the area (minor editorial changes have been made to the original message) stated:

> While offshore, we noted that major changes had occurred to the summit cone which had split down about 150 m in a big wedge and released a double lobed stream of lava to approximately the 1500 m altitude, heading down towards Cape Arkona on the western side of the Gotley Glacier.

It is possible that lava tubes were feeding lava to the base of the lobes.

Most recently, a plume was reported on 21 December 1996. Possible plumes from the island were identified by observers (N. Young & A. Tupper, pers. comm., April 1997). It seems in retrospect that these may have been "banner clouds" such as form as atmosphere passes over the top of mountains.

RECENT VOLCANISM ON McDONALD ISLAND

Pumice began to wash up on both sides of Elephant Spit on Heard Island in late December 1992, shortly after an earthquake, strong enough to be felt, on 18 December (Dr K. Green, pers. comm., December 1992). Small fragments of the pumice (and krill and penguin feathers) clogged the water intake of MV *Icebird,* which had to be cleaned to allow the ship to proceed. Four specimens, collected from Heard Island beaches, were analysed. A small, grey boulder from higher elevation than the others differed in composition and origin. It matched material collected in 1963 from "flotsam north of Heard Island" (Stephenson 1964), related to vast rafts of pumice released in the South Atlantic Ocean during the eruption in the South Sandwich Islands area in 1962 (Gass *et al.* 1963). This is probably the same material referred to by Dr Phillip Law (pers. comm., 19 August 1993) who saw rafts of pumice near Heard Island in January 1963. Stephenson (1972) presented an analysis (no. 54) of this material. The rock type is dacite characterised by relatively high silica (66.7% SiO_2 in the analysed sample) and high Na_2O/K_2O, resulting in plagioclase being dominant over orthoclase feldspar.

The other three samples have a quite different composition, unlike any lavas so far known from Heard Island. They are khaki-green colour and resemble McDonald Islands lavas (J. Sheraton, pers. comm., 10 June 1993). They indicate a submarine eruption but the source was not identified. Green also referred to the smell of sulphur gases, suggestive of a recent volcanic source and thus eruption. The volcanic rocks of Heard Island have been the subject of quite extensive study over many years by Tyrrell (1937), Stephenson, Nicholls, Clarke, Barling and Wheller, and their composition, distribution and source are thus reasonably well known. The rock type in the three specimens is phonolite, characterised by lower silica 54.6% SiO_2 in these samples, very high alkalies ($Na_2O + K_2O$). They are particularly enriched in Na_2O (10.9-11.3%), Ga, Nb, Ta and Zr, but relatively low in MgO, CaO, Ba and Sr. Phonolites from the McDonald Islands include fractionated types of similar compositions to the pumice samples (Clarke *et al.* 1983). Analyses of the fresh pumice stranded on Heard Island suggest it evolved over a long time in a magma chamber before eruption (Collerson *et al.* 1998).

Steam emission at the northern end of McDonald Island was seen from RSV *Aurora Australis* on 18 March 1997, at a distance of about 4 km. Steam arose from several sites, in the form of small clouds which moved quickly and seemed to come from a series of vents across the northern end of the island between The Needle and Macaroni Hill, north of Samarang Hill. Large quantities of volatiles were being emitted from a number of point sources and one fissure system on a large pile of apparently loose debris. The presence of steam and debris suggested that a volcanic eruption had recently occurred. The day was still and there was low cloud but visibility was quite good. There had been no reported eruption from the island before. The interpretation was strengthened by the 1992 reports of pumice on Heard Island beaches (Quilty 1995).

Since the initial sighting, Mr R. Williams (pers. comm., 2 April 1997) was on the FV *Austral Leader* on 2 April and saw evidence of extensive steam activity on McDonald Island from 25–30 km. He reported much vapour on a day when there was clear blue sky with only a small amount of medium and high-altitude cloud. The ship circumnavigated the island at 3–4 km and observed many "steam/smoke" clouds rising from the summit and flanks of the northern and middle parts of the island. Reports also referred to small black lava flows but, due to the amount of steam and cloud, it was difficult to tell whether the apparent activity was due to local fumaroles at roughly sea level or to lava flows descending gullies from higher altitude. The summit of the mid part of the island, which was the centre of the steam emission, had a clear ring of yellow-green deposit around it, which Williams took to be sulphur. No lava was seen being ejected into the air, nor were there any red glows. There was no evidence of volcanic activity on the southern part of the island. Wildlife was there in abundance and showed no sign of concern. Scientists on board another fishing vessel, FV *Pakura,* on 24 April also saw the steam plumes, and made videos and took photographs of the event. The *Bulletin of the Global Volcanism Network* (1999) carried a report for 1999 from scientists on board *JOIDES Resolution* for the Ocean Drilling Program.

GEOLOGICAL SIGNIFICANCE OF HEARD ISLAND

Heard and the McDonald Islands are young oceanic-island volcanoes which, together with the Kerguelen Islands 466 km to the northwest, are the only subaerial expressions of the dominantly volcanic and relatively shallow northern part of the submarine Kerguelen Plateau which has a geological history extending over 115 Ma (Davies *et al.* 1989). The geological histories of Heard and the Kerguelen Islands extend over the last 50 Ma while the McDonald Islands are very young, perhaps having formed within the last 100 000 years.

The geochemical compositions and mineralogy of the volcanic rocks from Heard Island and the McDonald Islands indicate they belong to the oceanic-island type of modern volcanoes, similar to many other Subantarctic islands, such as Kerguelen, St Paul, Amsterdam, Marion, Crozet, Bouvet, Tristan da Cunha and Gough Island (Tyrrell 1937, Lambeth 1952, Stephenson 1972, Clarke *et al.* 1983, Barling *et al.* 1994). This type of volcano is generally regarded as having formed as a result of plumes, or hotspots, which originate from over 600 km deep within the earth.

The Heard Island lavas have been recognised as two separate volcano-magmatic lineages, the basanitic to trachytic Laurens Peninsula Series (LPS) and the Big Ben Series (BBS) (Wheller & Barling 1992, Barling *et al.* 1994). The BBS contain relatively evolved basalts and trachybasalts as well as more primitive basanites formed by accumulation of olivine and clinopyroxene phenocrysts. Overall, the LPS appear to have formed by relatively simple, closed-system fractional crysallisation processes while the BBS seem to have experienced a more dynamic, mixing-controlled magmatic environment.

The two groups also display significant Sr, Nd and Pb isotope differences, with the LPS displaying more mantle-like characteristics. Helium isotope ratios also indicate separate origins, with the BBS having low MORB- and crust-like $^{3}He/^{4}He$ values of 0.4–8.4, while the LPS possesses "deep-mantle" values of 16.2–18.3 (Hilton *et al.* 1995).

The McDonald Island lavas are distinct from those of Heard Island by having phonolitic compositions, although their Sr and Nd isotopic values are similar to those of the BBS (Clarke *et al.* 1983, Barling *et al.* 1994). It seems unlikely that phonolites have been erupted from Heard Island; none were found among the numerous analyses reported by Barling *et al.* (1994), and those described by Tyrrell (1937) from Atlas Cove may well have been pumice clasts washed ashore following eruption from the McDonald Islands.

In general, the Heard Island volcanics cover the widest range of isotopic compositions known from any short-lived oceanic-island volcano system. The LPS possess a restricted range of compositions similar to those of other oceanic island volcanoes in the central Indian Ocean and suggestive of a deep mantle source. However the BBS cover a much wider range, which is similar to that of Kerguelen Island, more MORB- and crust-like in character, suggesting an origin in which very shallow mantle and crustal processes were important.

Heard Island and the McDonald Islands have been related to the broad-scale geological evolution of the Indian Ocean through their compositional, isotopic and temporal associations with other volcanic and submarine topographic features in the Indian Ocean, such as the Kerguelen Islands, the Kerguelen, Broken and Naturaliste Plateaux, and Ninetyeast Ridge, as well as the Rajmahal and Sylhet Traps in India and the Bunbury Basalt of southwestern Australia (Duncan 1978, Storey *et al.* 1988,1989, Davies *et al.* 1989, Weis *et al.* 1989, 1991, Barling *et al.* 1994). In general, this evolution implies the existence of a near-stationary mantle plume beneath the current Kerguelen Plateau for the last 135 million years, during which time about 60–120 million km^3 of basalt was generated as first India and then Australia separated from Antarctica to form the Indian Ocean basin (Davies *et al.* 1989).

There is debate, however, about the significance and role of the Heard and McDonald magmatism. Barling *et al.* (1994) suggested that Heard Island and the Quaternary volcanism of the Kerguelen Islands represent contemporaneous volcanism derived from the same large plume, as opposed to earlier proposals by others that Heard Island represents the latest manifestation of the plume. They also argued that the volcanic rocks of the BBS are the major products of the plume, with the plume-derived magma having been locally mixed with a high-$^{87}Sr/^{86}Sr$, low $^{206}Pb/^{204}Pb$ component which ultimately may have been sediment subducted into the mantle during the Proterozoic

prior to the formation of Gondwana. They further suggest that the LPS rocks represent a local mobilisation of lithospheric mantle which had been enriched as a result of earlier plume activity.

An alternative view is that the LPS derived from the plume, essentially free of any lithospheric interaction apart from shallow fractional crystallisation, and the BBS represent plume-derived magma which has been significantly contaminated by lithospheric mantle, retaining isotopic and incompatible trace element characteristics of Gondwana subcontinental mantle. This is mainly suggested by the high plume-like $^{3}He/^{4}He$ values of the LPS and the low, lithosphere-like values for the BBS revealed by Hilton *et al.* (1995). It is also consistent with the distribution of BBS Sr, Nd and Pb isotopic compositions between the plume source represented by the LPS and the Gondwana subcontinental lithosphere represented by ultrapotassic lavas from Gaussberg (Collerson & McCulloch 1983, Taylor *et al.* 1984).

In this case, the close isotopic similarities between the BBS and the Kerguelen lavas point to a significant role for lithospheric contamination in the formation of ocean island lavas, and the retention of subcontinental characteristics in otherwise "oceanic" lithospheric mantle long after continental dispersement has occurred. Moreover, it is important to note that this model does not require the presence of actual upper continental crust as part of the Kerguelen Plateau, as proposed by Watkins *et al.* (1974). It requires only the remains of continental lithospheric mantle, and this may be an expected consequence of the dispersal of the Antarctic, Indian and Australian continents away from the area in which the Kerguelen Plateau now lies.

Finally, while otherwise very similar in major and trace elements, the Heard Island lavas, particularly the LPS, possess unusually high levels of TiO_2 compared to other ocean island volcanic suites (Stephenson 1972). This is not only a fractionation effect, as the most primitive basanites also have high TiO_2, and must be inherited from the source. If the LPS does represent the uncontaminated plume source then its high-TiO_2 character may suggest that it is a relatively fertile plume and, therefore, not directly related to the long-lived and presumably now relatively depleted plume which gave rise to the broad-scale evolution of the Kerguelen Plateau.

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MANAGEMENT CONSIDERATIONS FOR THE HEARD ISLAND LAVA TUBE CAVES

by Kevin Kiernan and Anne McConnell

(with one text-figure and two plates)

KIERNAN, K. & MCCONNELL, A., 2000 (30:vi): Management considerations for the Heard Island lava tube caves. *In* Banks, M.R. & Brown, M.J. (Eds): *HEARD ISLAND PAPERS. Pap. Proc. R. Soc. Tasm.* 133(2): 13–22. ISSN 0080–4703. Department of Geography and Environmental Science, University of Newcastle, Callaghan, NSW, Australia; postal address 15 Summerleas Road, Fern Tree, Tasmania, Australia 7054.

Heard Island contains a system of lava tube caves in a largely pristine condition which are the best developed bedrock caves known in Antarctic or Subantarctic latitudes. They require special management, because of significant and sometimes fragile attributes associated with cave geomorphology, geology, hydrology, atmospheres, soils, microbiology, flora, fauna, vertebrate palaeontology, archaeology and safety considerations. Use for recreation, tourism or science may pose serious impacts on these cave environments. Restricted access under the Heard Island Wilderness Reserve Management Plan would be an appropriate management response.
Key Words: lava tubes, geoconservation, cave management, Heard Island, Subantarctic.

INTRODUCTION

A small complex of lava tube caves occurs at Azorella Peninsula in the Heard Island Wilderness Reserve and World Heritage Area, located in the southern Indian Ocean at 53°06'S, 73°24'E (fig. 1). Caves can be significant natural heritage assets because of their intrinsic value, their importance to ongoing natural processes, including ecological processes, or their instrumental values, such as their utility for scientific research, recreation or commercial tourism (ACIUCN 1996, Watson *et al.* 1997). This paper reviews the importance of the Heard Island caves, their vulnerability, safety issues associated with their presence, and their management under the Heard Island Wilderness Reserve management plan.

While these caves have long been known, they appear to have been treated as minor curiosities and paid little attention. Only recently has there been significant documentation of them (Kiernan *et al.* 1998). Because of their isolated setting and the very limited human intrusion, an opportunity, rare for such caves, exists to retain them in an essentially pristine condition. However, the caves are very close to Atlas Cove, where most people land on Heard Island. Increasing shipborne tourism poses risks to Subantarctic island environments (Cessford & Dingwall 1998), but government personnel can cause environmental harm in areas to which tourists are denied access, if appropriate management policies are not developed, understood and adhered to by all (Riffenburgh 1998).

Lava tube caves form when a flow of molten lava cools sufficiently to congeal and form a roof which remains after lava drains from the flow interior. Several modes of tube-flow initiation have been proposed (Ollier & Brown 1965, Peterson & Swanson 1974, Hon *et al.* 1994). Once established, tubes may enlarge by "thermal erosion" and localised mechanical incision by flowing lava (Coombs and Rowland 1994, Greeley *et al.* 1998, Kauahikaua *et al.* 1998) and through ceiling breakdown, especially where fallen blocks are swept away by still flowing lava (Kempe 1997, Kempe & Oberwinder 1997).

Lava tubes are known from Subarctic environments in Alaska, Iceland and Kamchatka (Jonsson 1991, Stefanson 1991, Slezin & Tsyurpa 1994), but the lava tubes on Heard Island represent the only record from Antarctic and Subantarctic latitudes (S. Harris, Arizona State University, compiler of the National Aeronautics and Space Administration's world data base on lava tubes, pers. comm. 25 June 1997). Elsewhere in the Indian Ocean, lava tubes are known from Mauritius and Reunion (Audra 1996, Middleton & Halliday 1997). The most extensive Australian lava tubes occur in the Undara lava flow in North Queensland (Atkinson & Atkinson 1995), and in the Newer Volcanics Province of western Victoria (Ollier & Brown 1965, Webb *et al.* 1982).

Lava tube caves may be important nature conservation targets, either in their own right as landforms or because of other values they contain. For example, lava tubes allow

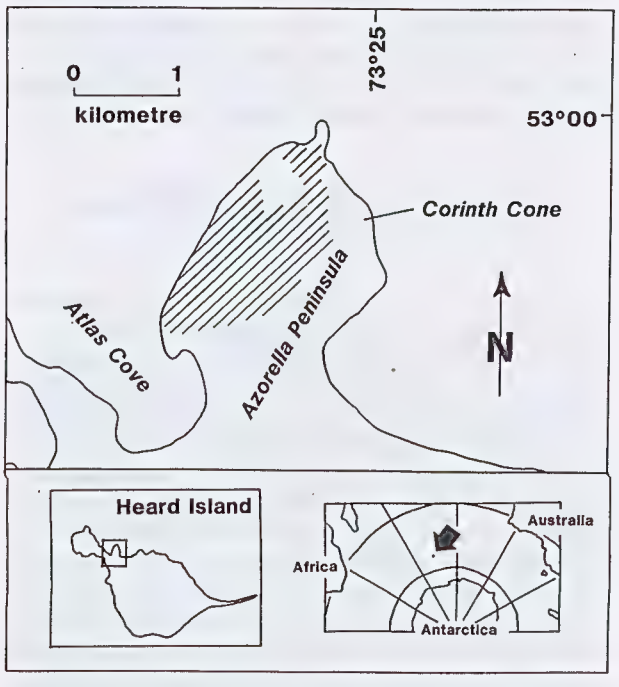

FIG. 1 — Location of Heard Island and Azorella Peninsula. Cavernous tube-fed lava flows occur in the shaded area.

insight into the mechanisms whereby long lava flows form on minimal slopes as basaltic plains and shields, and also contribute to understanding some aspects of interplanetary geology. Subsurface tubes permit discharge of large volumes of lava very efficiently over long distances with much less heat loss than at the lava surface; this allows the development of extensive, low gradient lava flows. (Cruikshank & Wood 1972, Hatheway & Herring 1970, Greeley 1991, Baloga *et al.* 1995). Caves provide buffered, dark habitats where life forms sometimes exhibit such adaptations as degeneration or total absence of eyes, lack of body pigment and long sensory appendages (Muchmore 1982, Briggs 1992, Crawford 1992, Howarth 1994). Over 50 cave-adapted invertebrate species have been recorded in Hawaiian lava tube caves (Howarth 1977).

Lava caves are complex, interactive natural systems and their management commonly needs to be integrated with that of the adjacent surface environment (Seesholtz 1997). Many cave resources are susceptible to damage or destruction, and non-destructive entry to some caves is not possible. Caves do not have a carrying capacity in the generally accepted sense (Aley 1975), because any recovery generally occurs over geological rather than human time-scales. Damage is cumulative, and often the first intrusions cause the most damage. A conservative approach to cave management can shield potential values even before their existence is recognised (Nieland *et al.* 1977). The precautionary principle caters for potential threats of serious or irreversible environmental damage, and requires that lack of scientific certainty should not be a reason to postpone measures to prevent environmental degradation. The precautionary principle is acknowledged in the Australian Natural Heritage Charter (ACIUCN 1996), which provides standards and principles for the conservation of places of natural heritage significance.

The inscription of the Australian Territory of Heard Island and McDonald Island (HIMI) on the World Heritage List on 3 December 1997 was based on its exceptional natural beauty, geoscientific values, and significant ongoing ecological processes. The caves of Heard Island are an important part of this World Heritage Area, but are not addressed by the present management plan for HIMI (Australian Antarctic Division 1995).

THE LAVA CAVES OF AZORELLA PENINSULA

Successful protective management of cave environments generally requires an understanding of the values known or potentially present, their likely sensitivity to disturbance and a decision as to the level of human impact acceptable. Acquiring an understanding of the values and the natural processes that sustain them that is sufficiently comprehensive to facilitate soundly based management decisions is commonly a lengthy procedure, even for readily accessible and well-researched caves (e.g. Manidis Roberts 1994). It is very much more difficult for remote, poorly known caves, where data gathering is difficult and expensive. Where management decisions nevertheless need to be made, some guidance can be gained by analogy with the most comparable cave environments elsewhere. In the paragraphs that follow, confirmed values of the Azorella Peninsula lava tubes are reviewed, and other values that may be present are identified by analogy with lava caves elsewhere. This approach is consistent with Article 5 of the Australian Natural Heritage Charter, which provides that the conservation of a place should take into consideration all aspects of its natural significance without unwarranted emphasis on any one aspect at the expense of others.

Geomorphology

The Azorella Peninsula lava tubes have been described elsewhere (Kiernan *et al.* 1998) and are merely summarised here. In common with many lava tubes elsewhere, these caves are associated with surface landforms produced by lava inflation, a process that results from the injection of mobile lava beneath congealed crust, physically raising the lava surface by hydrostatic pressure (Walker 1991, Mattox *et al.* 1993, Hon *et al.* 1994, Cashman *et al.* 1998). The longest accessible tube segment documented to date is ~200 m long, up to 8 m in diameter and lies at only a few metres depth. Strand lines and benches on the tube walls record successive levels of the internal lava flows, and variations in tube floor morphology record stages in their cooling (pl. 1), the breakout of tube-fed liquid lava beyond a stagnated flow and evidence of lavafall erosion. Small lava stalactites and stalagmites also occur, some extended by secondary minerals precipitated from seepage water. Some roof-fall blocks occur beneath intact ceiling linings, and lava stalagmites have formed on some fallen blocks, both implying breakdown during initial tube formation. Two open vertical volcanic conduits (OVCs) (Skinner 1992) occur near Corinth Head. OVCs are rare, as they are often rapidly filled by collapse and debris accumulation (Hatheway & Herring 1970, Jonsson 1991, Favre 1992, Halliday 1997). The only other OVC in Australia is at Mt Eccles in Victoria (Webb *et al.* 1992).

Study of these landforms on Heard Island remains incomplete. The morphology of lava tubes reflects their diverse geological influences, topographic settings, modes of genesis, stages of development and other factors. Caves and sinkholes can act as sediment sinks and retain wash from the surrounding landscape that may be important for palaeoclimatic reconstruction. Secondary cave minerals can reflect climatic or hydrological conditions or biological colonisation of caves and, hence, may allow insights into

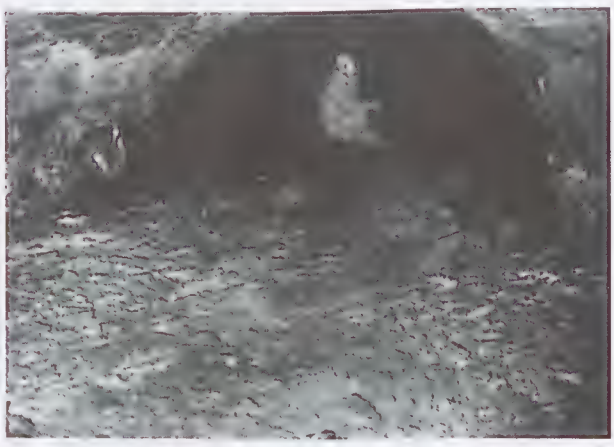

PLATE 1
Interior of a lava tube, central Azorella Peninsula. The flat floor is the product of incomplete drainage of lava from the tube.

palaeoenvironments and biological evolution. Caves in basalt tend to contain a greater range of minerals than do karst caves, due to contributions from the host rock and interactions with volcanic fumes, guano from cave-inhabiting biota and soils (Hill & Forti 1986, Pilkington & Segnit 1979, Webb 1986, Grimes & Watson 1995, Halliday 1995). Thick guano accumulations in one Heard Island lava tube (Brown 1957) have potential for mineralogical, dating and palaeoenvironmental studies.

Bedrock Geology

The volcanic geology of Azorella Peninsula is little studied. Lava tubes and related features can provide exposures of subsurface geological structures and rocks not otherwise accessible. Some lava layers exposed in these caves lack cooling crusts and have strings and lava dribbles stretching across the voids. This suggests the layers are not all individual flow units. Lava tubes can provide insights into volcanic plumbing and deep stratigraphy, eruptive histories, rates of effusion and flow duration, while vegetation casts or palaeosols may be encountered in cave walls (Wood 1992).

Palaeontology

Bone deposits in caves may be the remains of cave dwellers, their prey devoured in caves or victims of natural pit trap effects. Any bone deposits in caves or sinkholes of Azorella Peninsula are an unknown quantity, but these are likely sites for bones, given their occupation by penguins (Brown 1957). Bones may reveal extinct species, past patterns of animal distribution and broader environmental evolution (Wakefield 1964, Olsen & Wetmore 1976).

Hydrology

Layered lava, vertical joint systems and lava tubes are more prone to infiltration than most geological terrains. No detailed understanding exists regarding the hydrology of Azorella Peninsula, water quality or use of the groundwater by underground biological communities. There is abundant seepage into some of these caves, but concentrated flows are relatively rare, despite the shallow depths and high rainfall. Moisture on some cave walls is condensation rather than seepage, while some cave passages are remarkably dry. The caves offer potential for study of the hydrology of a lava flow in an unusual climatic setting.

Cave Atmospheres and Cave Climatology

Cave atmospheres are of scientific interest in their own right and are also an important influence upon some speleothems and fauna. No work has been undertaken on any aspect of the atmospheres and microclimates of the Heard Island caves. Cave temperatures are generally influenced by cave wall temperature, external conditions, passage configuration, entrance location, conduction through walls, and through the exchange of latent heat by condensation or evaporation. Some lava tubes remain warm due to geothermal heat release, while others function as cold air traps (Jonsson 1991, Halliday 1977, 1995). The Heard Island lava tubes are shallow and the overlying soils thin; hence, some surface-driven temperature changes are likely (Benedict 1977). An ice plug was recorded in one entrance in March 1997, when ice masses were at their seasonal minima; hence this plug may be permanent. Underground ice occurs in lava tubes in the Northern Hemisphere, but permanent underground ice is unrecorded from any other lava caves in the Southern Hemisphere or from caves of any other kind at southern latitudes equivalent to Heard Island.

Free air movement occurs in the more spacious and open lava tubes but is inhibited by blockages of rockfall debris, fine sediment and ice. Air movements may be caused by chimney and reverse chimney effects; the adjustment of the cave atmosphere to barometric fluctuations in the external environment; the gravitational drainage of air into single entrance caves; the resonance of air in large chambers (cave breathing); or other factors (Wrigley & Brown 1976). Interstices between lava layers may play a significant role in ventilation of these lava caves.

Atmospheric CO_2 levels may vary, due to the in-wash and decomposition of organic material and the degassing of infiltration waters. Light penetration, air quality and humidity are significant to cave biota. Four habitats are recognised in caves (entrance, twilight, transition and deep cave zones) with the most highly cave-adapted species occurring in the deeper and darker parts of caves. A fifth stagnant air zone enriched in carbon dioxide can be found in dead-end passages beyond configurations that trap water vapour or carbon dioxide, or where air intake has been precluded (Howarth & Stone 1990).

Pedology

There has been limited pedogenesis upon these young lava flows. The regolith over the caves includes reworked volcanic ash, while organic soil is related to the thick *Azorella* mounds and to nutrient inputs and burrowing by birds (Australian Antarctic Division 1995). This singular tube-fed lava flow landscape in Subantarctic latitudes may yield soil types unusual for lava tube environments. Soils have important implications for botanical colonisation and for the evolution of soil and cave fauna. Voids in cavernous lava sometimes initially allow free drainage and a steep hydraulic gradient directly downwards, but root penetration and the entry of nutrients may become inhibited as soil particles clog drainage routes (Howarth 1994). Some soils on Azorella Peninsula are relatively erodible, with potential for loss underground.

Microbiology

Reflective white dots on the ceilings of some of these caves appear similar to features elsewhere shown to be very large colonies of actinomycete bacteria. Bacteria also inhabit other cave niches. Elsewhere, bacteria and cyanobacteria that have the capacity to derive energy from reduction or oxidation of iron or sulphur compounds support food chains for cave invertebrates. Microbes have been implicated in the formation of some iron and manganese oxides, sulphur compounds and other cave minerals. The retention of pristine sites is important for work in these fields and on microbial diversity generally. Caves offer important opportunities for new understanding of the evolutionary relationships of bacteria and fungi. Models of possible life

on Mars are being developed through study of microbial communities in subsurface environments on Earth, while the discovery of chemical substances in cave microbes that are effective in fighting forms of cancer adds another dimension (Northup *et al.* 1997).

Botany

No botanical studies of the cave entrances has been undertaken (Bergstrom & Seppelt 1988, Scott 1990). Distinctive plant communities may develop in some tube-fed lava landscapes (Johnson *et al.* 1968), partly because water may rapidly be lost underground into subsurface void systems producing a degree of relative aridity. Young lava flows lack mature soil profiles that facilitate water retention, so the vegetation is often relatively xeric, regardless of climate. Special environments often exist in sinkholes where cold air is ponded, there is movement of air into and out of cave entrances, seepage water is concentrated or there is shelter from strong winds (Crawford 1992). Distinct local sinkhole communities may develop (Nieland *et al.* 1977, Joyce & Webb 1992); thus, 20 fern and 62 moss species, lichens and liverworts coexist at the Byaduk lava caves in western Victoria (Beaglehole & Learmonth 1957).

Zoology

The use of these caves by birds has left eggs within some, while Brown (1957) records a colony of rockhopper penguins (*Eudyptes chrysocome*) in another, and we know of no other lava tube area with such an occurrence. No systematic investigation of the invertebrate fauna of the Heard Island lava tubes exists but, by analogy with lava tubes elsewhere and a relatively diverse invertebrate fauna on the surface (Gressit 1970, Horne 1984, Dartnall 1995, Australian Antarctic Division 1995), there is the potential for biospeleological investigations.

Potential food enters these caves from the surface via gravity fall down entrances, entrainment by water or air flows, and carriage underground by animals. Potential energy sources underground also include penetrant plant roots, eggs, guano and carcasses. Shallow lava tubes are readily reached by seepage water rich in dissolved and fine particulate organic matter, which supports heterotrophic bacteria that may form lava tube slime. While organic inputs occur relatively evenly over time and space rather than in the stream-borne pulses found in karst caves (Howarth 1994), the community structure and bioenergetics of lava tubes and karst caves are broadly similar, apart from the nature of the energy source and the taxonomy of the biota (Crawford 1992). Surface climate and floristic diversity generally determine the rate of succession in lava caves, with the most diverse cave communities occurring in young, well-vegetated lava flows (Howarth 1994).

These lava tubes are very young, but cave-obligate fauna has been found in other young lava tubes, where species have been able to evolve in earlier caves and disperse through voids such as those between lava layers. There can be an ongoing cycle of void formation and occupation, blocking of voids by collapse or clogging with the residues of rock decomposition, and the migration of faunas into newer void systems (Crawford 1992). New lava flows reset biological succession both above and below ground; successive lava flows provide new subsurface void systems, offering near-surface habitat that may be colonised by fauna from older, deeper lava flows. This upward extension of potential subterranean biospace and succession in lava caves contrasts with the situation in karst caves, where potential biospace is formed at progressively greater depth as streams cut deeper, but in both cases the new caves may be colonised by older faunas (Howarth 1994). The better developed shallow intermediate void spaces that occur in lavas may initially be penetrated by plant roots that are important energy sources for cave invertebrates. Ash may have clogged some infiltration routes here, while the herbaceous vegetation gives less potential for deep root penetration than occurs in the tropical rainforest lava terrains, where highly developed lava cave faunas have been recorded. If the earliest eruptions on Azorella Peninsula are comparable in age to those on the adjacent Laurens Peninsula, then subjacent void space is probably Holocene, perhaps limiting the potential for a well-developed troglobitic fauna. Limestone underlying the lavas of Heard Island exhibits some karst landforms (Australian Antarctic Division 1995) and provides another possible source for cave adapted fauna to colonise the lava tubes (Crawford 1992).

Archaeology

There is no evidence of prehistoric human occupation of Heard Island, but the historical archaeology includes sealing and scientific sites. Lazer & McGowan (1990) recorded occupied caves on Heard Island but did not investigate the lava tubes. Caves have the potential to contain structures such as cleared areas, walling, entrance modifications or sediments that incorporate evidence of earlier human use and adaptation.

CAVE MANAGEMENT CONCERNS

The growing world literature on cave management is related primarily to karst caves but it contains some elements adaptable to lava tube management (Davey 1984, Kiernan 1988, Watson *et al.* 1997). Lava caves are also sensitive to human impacts. For example, lava stalactites and stalagmites formed in a volcanic eruption cannot regenerate, unlike the continued growth of stalactites in a karst cave. But important differences between lava caves and karst caves relate to fundamental differences in the morphology, genesis and functioning of these two types of cave. Lava tubes form shallow and predominantly horizontal caves, successive lava flows producing new primary cavities close to the surface, whereas karst caves evolve as integral parts of hydrological systems, subterranean waters dissolving out cave passages at increasing depth in a rock mass that may otherwise lack many open fractures. Lava layering facilitates the circulation of water and air, energy, biota and nutrients, and the influence of outside air circulation on shallow and short lava tubes contrasts with more buffered deep karst caves. Lava layers, sealed behind melted tube wall and roof linings, offer additional biospace where troglobitic invertebrates occupy interconnected cavities that are too small for human entry (Crawford 1992, Chapman 1993).

Potential for Damage to Cave Resources

If the primary goal of managing a cave is the protection of its intrinsic values or natural process values, then management intervention becomes necessary only in the event of unnatural perturbations. If the only value of a cave is perceived to be its instrumental value for science, recreation or commercial tourism, its intrinsic or natural process values may be compromised by such use. The environmental harm can either be accepted, or management may intervene to reduce it. The nature of the activity conditions the kind and degree of damage.

Large bedrock and geomorphological features in caves are relatively robust, but smaller features are more vulnerable. Shelly pahoehoe lava blisters and florets of aa lava that floor some passages at Heard Island are very susceptible to breakage by visitors, lava stalactites can be broken, soft clastic speleothems and sediments can be trampled and eroded and features buried by sediment that is disturbed (Nieland *et al.* 1977, Halliday 1995). Over-zealous geological collection (amateur, scientific or commercial) has taken a toll in some other Australian lava caves and could do so here (Joyce & Webb 1992). Any applications for geoscientific collecting from these caves need careful assessment, recognising that multiple access may compound damage. The potential for sharing samples and lodging of specimens in a sample bank should be considered.

Bone deposits in earthy matrix are commonly dismissed as "just dirt" by casual visitors. Protection is necessary to minimise crushing, erosion and spreading of sediment deeper into the cave environment by foot traffic, and to protect the entrance vegetation. Bones are also easily damaged by the instigation of drainage changes that lead to erosion, collection, artificially induced microclimatic changes that alter weathering processes, or changes in the moisture status of sediment matrix or the chemistry of water that reaches bone deposits. Activities of fossil collectors, some commercially motivated, are difficult to manage in remote localities.

Environmentally detrimental changes to the flow regime and quality of the groundwater may be caused by human activities above or below ground. In lava tubes, the void systems form natural pipes, permitting rapid transmission without the natural filtering and purification found in geological terrains where fabric selective porosity predominates. Water in lava tubes is important to maintaining natural heritage values, including biological habitats and the continued growth of secondary speleothems.

Cave atmospheres and microclimates may be altered by blocking or digging open entrances or passage constrictions, changing fauna habitats and preventing research into natural cave microclimates. A 1°C increase in cave air temperature raises its water vapour capacity by 8% and can result in a ten-fold increase in evaporation, with adverse implications for some secondary speleothems and invertebrate cave faunas (Williams 1975). Even human body warmth can temporarily but appreciably change cave temperatures. Air quality changes are compounded by carbide lamps, candles and smoking cigarettes underground.

Even scientific investigation of the cave ecosystems risks the environment; for example, the colony of penguins in an Azorella Peninsula lava tube is considerably disturbed when humans intrude into their dark and confined underground home (Brown 1957). While an invertebrate biology in the lava tubes may add to the faunal values, visitors have potential to impact upon invertebrate fauna species survival, because the total population of cave species can be very small. The loss of even a few individuals may trigger extinctions or accelerate the pace of genetic drift (Howarth 1981). Cave fauna may react to changes in food supply, and some materials left by visitors are readily colonised (Spate & Hamilton-Smith 1991). Floor-dwelling and aquatic invertebrates and their environment may be trampled and impacted, with species restricted to particular substrate types being most vulnerable (Eberhard & Hamilton-Smith 1996). A variety of management responses may help, such as delineating substrate protection zones and confining foot traffic to defined paths. Some cave fauna is disturbed by torchlights or unusual noise. Howarth (1992) reports of Hawaiian lava tubes:

> Our field data show that, other factors being equal, species diversity and population levels of cave organisms is inversely proportional to the level of visitation and human disturbance.

Much invertebrate cave fauna is almost "aquatic" in character. Resolution VI.5 from the 1996 Ramsar Convention on the Conservation of Wetlands and Waterfowl determined that subterranean karst and cave hydrological systems should be added to the Ramsar wetland classification system. Because many cave faunas are highly susceptible to changes in atmospheric humidity and some are dependent upon high CO_2 atmospheres, excavations for access into further caves or cave passages is unwise.

Undisturbed microbial communities could be changed by human importation of foreign microbes and organic matter, in such forms as skin flakes, food and lint, that displace organisms adapted to highly oligotrophic conditions (Northup *et al.* 1997). The relatively pristine condition of the Heard Island lava caves is an important consideration.

Visitors to these caves disturb vegetation in entrances, sinkholes and along access routes, accelerating soil erosion. The sinkholes host visually delightful sunken gardens, which it would be a shame to see disfigured (pl. 2). The *Azorella selago* mounds on Azorella Peninsula are particularly susceptible to trampling, and imprints can last for a long time. Experienced individuals can reduce vegetation damage using suitable foot placements and footwear, but not all potential visitors have had this experience. Small bedrock inflation landforms, themselves vulnerable to breakage,

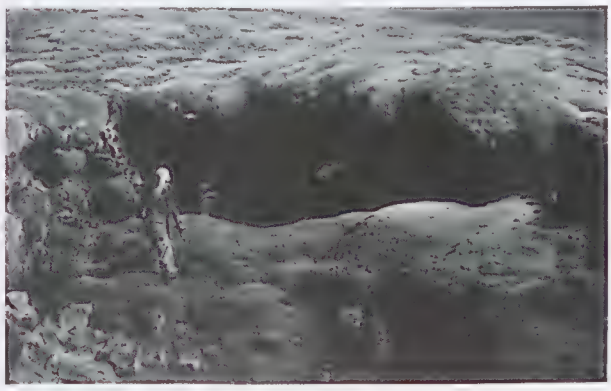

PLATE 2
Vegetation, predominantly Azorella selago, *in a sinkhole that contains the entrance to a lava tube cave.*

sometimes provide alternatives to walking on the vegetation; elsewhere, bare soil surfaces may be riven by bird burrows that collapse underfoot.

Damage may be caused to archaeological resources by foot traffic, souveniring, or various other activities — in some cases publication of information concerning archaeological resources in lava caves has led to looting (Howarth 1992). Visitors to the Azorella Peninsula caves need to be aware of the sorts of cultural heritage features they might inadvertently disturb.

Potential for Damage to Human Visitors

Cave environments are often unforgiving of the ill-prepared, inexperienced or incautious. The deep OVCs have sloping entrance funnels of loose scoria that are potential "ant traps" for people who do not exercise caution. Underground, steep slopes, slippery surfaces, shadowy deep holes or shafts all offer the potential for accidents, while some cave ceilings are locally unstable. The risk of hypothermia in the event of injury and delayed rescue is very high. The Australian Speleological Federation Inc. (1990) cave safety guidelines, although not geared directly to the Heard Island environment, provided valuable general advice.

Cave rescue is a specialised enterprise, and generally very time consuming. Where accidents occur remote from trained rescue personnel, inexperienced personnel may be forced to attempt rescue, posing a serious risk of additional people becoming trapped or injured. Rescue would most likely be a protracted affair, even without physical entrapment that might require specialised equipment to lift rocks or the need to retrieve a victim from beyond a narrow passage constriction. The environmental costs could be great.

While the potential risks to human health posed by such known cave hazards as contaminated water, diseases or radon gas are probably very low, their consideration forms part of the duty of care of any cave management authority. For example, the potentially fatal disease histoplasmosis is a known hazard for cavers who visit bat roosting sites but is especially suited to avian habitats (Ibister *et al.* 1976, Hunt *et al.* 1984, Harden & Hunt 1985). The fungus *Histoplasmosis capsulatum*, which causes the disease colonises soil contaminated by faeces, and infectious spores may be inhaled when this is disturbed. Histoplasmosis is generally considered a hazard of the tropical and temperate environments, but the potential for it to exist in Subantarctic caves is untested, since no other caves inhabited by large bird populations have been recorded from Subantarctic latitudes. The radioactive gas radon, produced by the decay of uranium, and its microparticulate daughter products occur in some karst caves and may contribute to lung cancer. Casual visitors to caves are unlikely to accumulate a harmful dose (Solomon *et al.* 1996) but, given higher uranium concentrations in volcanic rocks than in limestone, the potential may exist for radon levels to be higher in less well ventilated passages.

Implementing Management of the Heard Island Lava Tubes

Protection of the HIMI environment is provided for by the *Territory of Heard and McDonald Islands Environment Protection and Management Ordinance* 1987, the *Environmental Protection (Impact of Proposals) Act* 1974, the *Australian Heritage Commission Act* 1975 and the *World Heritage Properties Conservation Act* 1983. Other legislation relevant to management decisions that affect lava cave fauna includes the *National Parks and Wildlife Conservation Act* 1975 and, potentially, the *Endangered Species Protection Act* 1992. Heard Island is administered by the Australian Antarctic Division in accordance with a management plan that sets out the vision (Australian Antarctic Division 1995):

> Acknowledging the outstanding natural qualities of the Territory of Heard and McDonald Islands, and its great importance to the ecosystems of the Southern Ocean, management of the Territory will allow natural processes to proceed with minimal human intervention and will assign highest priority to conserving its environment, its value to research and its unique cultural heritage.

The present edition of the plan designates several seldom or never visited *Restricted Access Areas* that have been established as important scientific reference points providing as near to natural conditions as possible, to remain free from human interference except for essential management or compelling research purposes. The criteria upon which research within a *Restricted Access Area* might be considered "compelling" are not spelt out in the management plan. The Plan also provides for the designation of *Specially Protected Areas* to enable closure of part of the Territory to otherwise permitted uses through the permit system, in order to protect sensitive phenomena or for human safety. Under the present plan the area around the caves is zoned as a *Wilderness and Heritage Area* with cited values of little recent human impact. However, Azorella Peninsula adjoins a *Main Use Area*, which puts potential visitor pressure on the lava caves. While the very remote setting of Heard Island inhibits human activity, it also militates against effective site management. Potential use scenarios involve casual recreational visits by expeditioners, organised cave tourism and scientific investigations.

The impact of recreational caving parties depends upon the number of participants, their attitudes, experience and skill. The attractiveness of the caves as venues for recreation may be diminished if important attributes are degraded. Accrued recreational impacts recognised here in March 1997 were localised but included trampling of entrance slopes, litter and damage to vegetation along access routes. The Australian Speleological Federation (1995) has developed a set of minimal impact guidelines for caving which acknowledge that even experienced cavers can have adverse environmental effects, that every trip has an impact and that its real worth should be carefully assessed. Any permitted entry to the Azorella Peninsula caves should be conditional upon compliance with these guidelines at a minimum, and with draft guidelines for the protection of microbial communities in caves presented by Northup *et al.* (1997).

Sensitive caves generally fare best when their existence simply remains unknown to potential users. The American National Speleological Society (NSS) formally discourages

reporting recreational use of Hawaiian lava caves (Howarth 1992). Deflecting visitors towards more robust caves can be useful but is a hazardous strategy where other more sensitive caves occur in close proximity, because visitors may stray into the wrong cave. Gating cave entrances may generate significant environmental impacts and is a last resort. Even very basic stringline delineation of pathways is probably undesirable in caves frequented by penguins.

As venues for recreational caving, the relatively small caves of Azorella Peninsula offer little more than the possibility of satisfying casual curiosity or an opportunity to "collect" a cave experience from an exotic locality — they do not offer a quality caving experience. Given the other values that may be compromised and the range of alternative recreational opportunities available on Heard Island, it seems inappropriate to exploit the limited recreational caving potential offered by the lava tubes. They deserve better than to be treated simply as underground gymnasiums or playgrounds.

At least one tourist operator has already expressed interest in using these caves as attractions for shipborne tourists, despite the lack of any documentation regarding the extent, potential attractions, environmental sensitivities or safety of the caves. Most caves used for tourism have been "hardened" through the construction of walkways and protective infrastructure, but significant environmental impacts have still been generated (Williams 1975, Kiernan 1988). Where tourism occurs without the establishment of hardening infrastructure, the movement of visitors is unconstrained and floor surfaces are unprotected. In the absence of an effective management presence on site, a tourist guide is an obvious point of contact through whom environmental messages might be conveyed from a management authority to cave visitors, but for this to be successful the guides themselves must be fully conversant with the very special values and sensitivities that caves may hold and committed to their preservation. If the ASF minimum impact caving guidelines were adopted, the maximum caving party size of four might seem economically unattractive and is unlikely to provide an adequate economic return to fund protective infrastructure.

Another hazard posed simply by the proximity of the caves to the main use zone was illustrated during shipboard discussions prior to landing a very large party for the commemoration of the 50th anniversary of ANARE at Atlas Cove. It was proposed by one participant that the caves were close enough to provide useful emergency shelter should weather conditions or mechanical problems prevent the party being returned to the ship at the time planned. Although this proposal was recognised by others to be inappropriate, it highlights the need for appropriate management policies to be developed, understood and adhered to by all.

As interesting and worthwhile as scientific research can be, it has the potential to cause environmental impacts over and above the "base load" a cave environment must endure simply from people being in it at all (Kiernan 1997). Few scientists are also experienced minimal impact cavers and yet they may be involved in initial exploration, when the most serious damage is often caused. Special risks arise even in compiling a comprehensive cave map. More specialised studies involving collection of cave fauna, fossils or minerals, or the installation of scientific apparatus, can also pose risks, and finite resources are depleted where cave sediments are excavated. Often, researchers in one discipline act as if oblivious to other values, perhaps making an unwarranted assumption, consciously or otherwise, that their own field is of greater importance than any other. The real worth and purpose of any proposed research and its environmental impact all require careful scrutiny.

Environmental impact statements for scientific research are required under the management plan but must be properly assessed by qualified specialists and not merely be exercises in fulfilling bureaucratic requirements. At the same time, any cave manager must assess whether decisions by higher powers are likely to be proper professional decisions founded on scientific probabilities or are more likely to be political or legalistic determinations. This can sometimes lead to the unacceptable situation where managers may feel compelled to counter pressures for inappropriate use by allowing research that itself can reasonably be expected to involve serious degradation of a resource, compromising both their own professional standards and the environments in their charge.

CONCLUSIONS

The rare opportunity exists on Heard Island to retain a small system of lava caves in an essentially pristine condition, but application of the Precautionary Principle is required:

(1) Given the management concerns, the World Heritage status of Heard Island and its designation as a Wilderness Reserve, the adoption of a policy aimed at safeguarding all the natural values of the lava caves to the maximum possible extent would be appropriate. We consider that according primacy to respect for the intrinsic values of these caves should be the starting point for cave management on Heard Island.

(2) If the caves are left undisturbed by humans and the protection of their intrinsic or natural process values is given priority over their instrumental value, then scientific research and management intervention are not likely to be "essential". In our view, active management is only likely to become "essential" if it is decided to exploit the caves in some manner, thus generating a need to fully understand cave resources and their vulnerability, in order to develop means for minimising environmental harm.

(3) Entry to the caves, in order to obtain sufficiently detailed information as to allow informed in-cave management decisions, would inevitably imply some irreparable damage. True adherence to the vision set out in the management plan for the Heard Island Wilderness Reserve may not be consistent with permitting that damage to occur.

(4) Some of the research questions raised earlier might equally well be addressed in other lava cave systems elsewhere that have already been subject to human impact. Similarly, experimental strategies for protection of cave environments would more appropriately be trialed elsewhere, in preference to exposing these caves to unnecessary irreversible damage.

(5) Notwithstanding some ambiguity in the *Restricted Access Area* concept as it presently stands, we believe this is the most appropriate zoning available for the lava tubes under the HIMI management plan. If necessary, they could be designated a *Specially Protected Area* until the management plan is revised.

(6) Effective protection of these caves is unlikely to be achieved unless there is consultation and agreement regarding its desirability, and understanding of the impact likely to be

caused by visitation. Because no management presence is maintained on Heard Island, merely prohibiting entry to the caves is not likely to secure their long-term protection. It needs to be supplemented by highlighting other more robust and scenically spectacular sites as more desirable venues for visitors. We applaud initiatives of this kind already being pursued by the Antarctic Division.

(7) While we do not endorse visitation, if it is to be permitted it should be restricted in the first instance to parties involved in proper scientific assessment of the lava tubes that is directed towards meeting genuine management needs, not just opportunistic sojourns. It should be undertaken only by persons experienced in conducting research in caves, complying with the ASF minimal impact caving guidelines as a minimum requirement, and directed towards development of a special management plan for the lava tubes. Any underground recreation or tourism should be preceded by the installation of necessary protective infrastructure.

Effective protective management of caves is seldom easy, because there are important yet sensitive values and complex competing demands. At Heard Island, the few demands that exist should in theory be more simply dealt with than is the norm. The wilderness character and natural value of the Heard Island caves are enhanced by the fact that they occur in one of the wildest and most remote places on Earth. If the opportunity exists anywhere for a small set of caves to be left untrammelled by humankind, then this could be the ultimate place, if human curiosity, scientific ambition, economic pressures or politics will allow it to be achieved.

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THE BIOGEOGRAPHY OF SHALLOW-WATER MACROFAUNA AT HEARD ISLAND

by Graham J. Edgar and Harry R. Burton

(with two tables)

EDGAR, G.J. & BURTON, H.R., 2000 (30:vi): The biogeography of shallow-water macrofauna at Heard Island. *In* Banks, M.R. & Brown, M.J. (Eds): *HEARD ISLAND PAPERS. Pap. Proc. R. Soc. Tasm.* 133(2): 23–26. ISSN 0080–4703. School of Zoology, University of Tasmania, GPO Box 252-05, Hobart, Tasmania, Australia 7001 (GJE); Australian Antarctic Division, Channel Hwy, Kingston, Tasmania, Australia 7050 (HRB).

Collections of 23 macroinvertebrate taxa associated with *Durvillaea antarctica* holdfasts and 58 invertebrate taxa associated with artificial substrata collectors are described from shallow-water and intertidal habitats at Heard Island. The fauna sampled possessed strong biogeographic affinities with the Kerguelen Island fauna and, to a slightly lesser extent, the fauna recorded at Macquarie Island but negligible affinity with the Antarctic. Experiments involving the offshore tethering of *D. antarctica* holdfasts indicated that epifaunal invertebrates rapidly abandoned detached holdfasts, but that the few species surviving after one day could probably survive long periods adrift.

Key Words: shallow-water macrofauna, invertebrate taxa, *Durvillaea antarctica*, Subantarctic fauna, Heard Island.

INTRODUCTION

Heard Island, Kerguelen Island and Macquarie Island occupy pivotal geographic positions in the Southern Hemisphere with respect to the testing of biogeographical hypotheses. While Heard Island and Kerguelen Island are connected geographically by the relatively shallow Kerguelen–Gaussberg Ridge (<400 m depth; Houtz *et al.* 1977), these islands are separated by a steep water-temperature gradient (≈4°C) due to the intermediate location of the Antarctic Convergence. Kerguelen Island has a similar oceanographic climate to Macquarie Island but is geographically separated by long distance and deep water. Consequently, a knowledge of the affinities of Heard Island, Kerguelen Island and Macquarie Island marine biotas should allow the relative influences of water temperature (and its correlates) and the dispersal abilities of Subantarctic species to be assessed. In contrast to the shallow-water faunas of Kerguelen Island (Arnaud 1974) and Macquarie Island (Simpson 1976, Lowry *et al.* 1978, Edgar 1987, O'Hara 1998), which have been relatively well studied, very little has been reported on the Heard Island macrobenthos (Simpson 1988). Shallow inshore species have only been collected in the area at a single BANZARE station in 1929 and as a result of *ad hoc* collections by ANARE expeditioners (Dell 1964), while Smith & Simpson (1985) provided a brief description of intertidal zonation patterns.

The presence of any species at Heard Island will be the result of either vicariant or dispersal processes (Edgar 1986, O'Hara 1998). Thus, species either have a long past association with Heard Island and its associated landmass or have arrived comparatively recently by benthic or pelagic migration. Knowledge of the relative importance of these processes has applied as well as theoretical importance. Information on the timescale of colonisation rates is crucial if, for example, the rate of recovery of the island's biota following a catastrophic disturbance, such as an oilspill, is to be predicted.

The wide distribution of many benthic species around the Subantarctic region has led many biogeographers to consider that dispersal, in particular the dispersal of benthic species associated with drifting seaweeds, is more important than vicariance in explaining species distributions for shallow-water Subantarctic taxa (Knox & Lowry 1977). Detached plants of the giant kelp *Macrocystis pyrifera* are widely considered the main vector contributing to this process (Beurois 1975, Edgar 1987). *Macrocystis pyrifera* does not occur at Heard Island, hence the hypothesis that *M. pyrifera* greatly enhances dispersal rates can be tested, using the prediction that the lack of *M. pyrifera* at Heard Island has inhibited the colonisation of epipelagic immigrants, and that the island is faunally depauperate as a consequence.

Alternatively, a second large macro-algae that drifts long distances, *Durvillaea antarctica,* may be responsible for transporting much of the benthic fauna to Heard Island, and from Heard Island further eastwards. Drifting *D. antarctica* plants are approximately 20 times more abundant than *M. pyrifera* plants in the open sea, with one estimate of 70 million kelp rafts drifting in the Southern Ocean (Smith 1998). In order to test the hypothesis that *D. antarctica* provides a major dispersal vector, *Durvillaea* holdfasts were detached from the shore and tethered offshore at Heard Island, with survival of associated invertebrates assessed after three months adrift. If *D. antarctica* provides an important dispersal mechanism, then numerous species are predicted to survive in association with detached plants.

METHODS

Mobile macrofaunal species were collected by attaching artificial algal habitats (≈70 g clumps of tanikalon rope fibre) to individual bricks, placing the bricks into the field at Heard Island and retrieving them with associated animals after three months submergence. Invertebrates >0.5 mm sieve-size were extracted from artificial algal habitats by sieving the preserved samples using the methods described in Edgar (1993). Four artificial habitats were placed in lower intertidal rock pools at Atlas Cove on 27 November 1987, and six artificial habitats at 8–9 m depth in Corinthian Bay on 21 November 1987.

Survival of benthic animals when associated with drifting *D. antarctica* plants was assessed by prising plants from rocks in the lower intertidal zone at Atlas Cove, attaching the plants to ropes, and then slowly towing the plants

≈500 m offshore. A preliminary trial indicated that whole plants attached to lines created too much drag for anchors, hence holdfasts were separated from fronds and tethered at the sea surface to anchored buoys. This process was undertaken on 20 November 1987, with four of the tethered holdfasts collected for faunal analysis the next day. Two holdfasts were lost to wave action during the study, with the remaining two holdfasts collected after 93 days afloat. Holdfasts (4 replicates) were also collected as faunal controls from the shore at the start (20 November 1987) and end of the experiment (21 February 1988).

In order to assess whether recruitment was occurring on tethered holdfasts, four replicate holdfasts were defaunated by submersion in freshwater for ten minutes at the start of the experiment before offshore tethering (Edgar 1992). Two of these recruitment control holdfasts were lost through wave action and two collected at the end of the experiment.

On collection, all holdfasts were carefully placed into plastic bags and formalin added. Animals were later separated from holdfasts in the laboratory by pouring the washed contents of the bags through a 0.5 mm sieve after the holdfast had been broken apart; animals retained by the sieve were counted under a binocular microscope using the same methods as for artificial algal habitats.

RESULTS

A total of 58 macrofaunal species was collected from artificial algal habitats during the study (table 1), and a total of 23 species was collected from *Durvillaea* holdfasts, including ten species not collected from artificial habitats (table 2). The great majority of Heard Island taxa identified to species have been recorded previously from Kerguelen Island, with many species also recorded from Macquarie Island. In contrast to this Subantarctic affinity, no species were collected that possessed a Heard Island/Antarctic distribution.

The level of endemicity of the Heard Island benthos does not appear high. Amongst the five animal groups fully identified by taxonomists (Amphipoda, Isopoda, Tanaidacea, Mollusca and Echinodermata), only the gastropod *Laevilittorina heardensis* and the isopod *Limnoria carptora* are presently regarded as endemic. A further 12 species (31%) could not be assigned to known taxa. Most of these species probably occur in other Subantarctic locations but were not fully identified because specimens were immature or the wrong sex for adequate species determination.

Few animals survived in association with tethered *Durvillaea* holdfasts, even for 24 hours adrift (table 2). After the rapid initial population decline, four species (*Hyale hirtipalma, Limnoria carptora, Laevilittorina heardensis* and Oligochaeta sp. 1) persisted in low numbers on holdfasts until the conclusion of the experiment. Three of these species were collected from defaunated holdfasts tethered as settlement controls, hence recruitment as well as *in situ* survival probably contributed substantially to numbers collected on tethered plants, although some animals inhabiting deep cavities may have survived the freshwater defaunation process. The amphipod *Paramoera austrina* f. *kergueleni* greatly increased numbers on tethered holdfasts, presumably as a result of recruitment, while a second amphipod, *Probolisca ovata,* was collected solely on defaunated plants.

DISCUSSION

The small collections described here indicate that macrofaunal species richness at Heard Island is moderate rather than depauperate, with 42 macrofaunal species collected from four artificial habitats at Atlas Cove and 38 species amongst six habitats at Corinthian Bay. By comparison, the number of species associated with four artificial habitats of similar construction in other regions were 32 in a *Laminaria* kelp forest at Millport, Scotland (G. Edgar, pers. obs.) and 39 in Langebaan Lagoon, southwestern Africa (G. Edgar, pers. obs.), and ranged from a mean of 20 in the Bathurst Harbour estuary to 70 in Port Davey embayment, southwestern Tasmania (Edgar 1991). The absence of *Macrocystis pyrifera* at Heard Island does not appear to have substantially depressed the diversity of the shallow-water fauna.

Although Heard Island is located south of the Antarctic Convergence, the associated shallow-water macrobenthos has clear Subantarctic rather than Antarctic affinities. Geographic position clearly has a much greater biogeographic influence on the local marine fauna than contemporary climatic conditions. The slightly stronger affinities of the Heard Island benthos with Kerguelen Island (17 taxa) than Macquarie Island (13 taxa) also indicate that geographic connections have a predominant role in influencing the composition of the Heard Island benthos. Moreover, the much stronger biotic relationships with Macquarie Island than with the geographically closer Antarctic continent indicate that dispersal processes mediated by the West Wind Drift have greatly influenced the composition of Heard Island benthos.

A large proportion of the species present at both Heard and Macquarie Islands (e.g. *Hyale hirtipalma, Anasterias mawsoni* and *Paramoera austrina)* lack pelagic larval stages, hence transportation by epipelagic drift probably has contributed to the dispersal of these taxa. Such species may have dispersed in association with drifting *D. antarctica* holdfasts; however, the majority of taxa were probably not transported in this way. Although the experiments described here were extremely limited in terms of replication and controls, and should therefore be regarded as preliminary, initial survival of taxa in association with detached *D. antarctica* holdfasts was very poor. The majority of individuals and species emigrated from *D. antarctica* holdfasts within one day, whereas most species present on tethered *M. pyrifera* holdfasts survived for >191 days at sea in experiments off Tasmania (Edgar 1987). Thus, despite the great abundance of *Durvillaea* rafts in the Southern Ocean (Smith 1998), *D. antarctica* probably provides a relatively poor vehicle for dispersal in comparison with *M. pyrifera.* Long-term survival of *Laevilittorina heardensis* on tethered holdfasts nevertheless indicates that *D. antarctica* may play an important role in the dispersal of a few intertidal invertebrate taxa. Species surviving for even one day at sea are probably capable of surviving long periods adrift. We note, however, that *L. heardensis* has not travelled long distances from Heard Island, as it is an endemic species, with the congener *L. caliginosa* abundant at Macquarie Island.

Additional support for the hypothesis that species disperse more often in association with *M. pyrifera* than with *D. antarctica* is provided by published descriptions of holdfast faunas at Heard Island (table 2), Kerguelen Island (Arnaud 1974) and Macquarie Island (Smith & Simpson 1995, 1998). Only three species, *Probolisca ovata, Omalogyra*

TABLE 1
Mean abundances of invertebrates collected from artificial algal clumps placed in Atlas Cove and Corinthian Bay

Taxon*	Distribution†	Locality		Taxon*	Distribution†	Locality	
		Atlas Cove‡	Corinthian Bay§			Atlas Cove‡	Corinthian Bay§
Amphipoda				Mollusca (cont.)			
Cerapus oppositus K.H. Barnard		4.3	2.0	*Onoba* sp.		1.5	0.5
Gitanopsis squamosa (Thomson)	K,M	5.8		*Zalipais* sp.		6.0	
Hyale hirtipalma (Dana)	K,M	0.5	1.5	*Lissarca rubrofusca* Smith	K		153.2
Oradarea tridentata K.H. Barnard	K	23.5		*?Hemiarthrum setulosum* Dall	K,M	0.3	
Paramoera austrina f. *kergueleni* Bellan Santini & Ledoyer	K	102.0	19.7	Brachiopoda			
Probolisca ovata Stebbing	K,M	256.5	3.0	Indet. sp.		0.3	
Schraderia gracilis Pfeffer	K,M	1.0	0.5	Arthropoda			
Gammaropsis sp.		3.3		Acarina sp. 1		3.7	18.7
Ischyrocerus sp.		23.5	0.2	Acarina sp. 2		0.3	0.3
Jassa sp.		14.5	0.8	Pycnogonida sp. 1		0.5	
Metopoides sp.		0.3		Pycnogonida sp. 2			0.2
Paramoera sp.		19.8	1.4	Pycnogonida sp. 3			0.5
Podocerus sp.		15.0	1.0	Echinodermata			
Isopoda				*Anasterias mawsoni* (Koehler)	M	0.8	
Caecianiropsis ectiformis (Vanhoffen)	K	47.5	0.2	Cnidaria			
Califanthura pinquoin (Kensley)		0.8	0.5	Actiniaria sp.		0.3	
Cassidinopsis emarginata (Guérin-Menéville)	K,M	0.5	1.0	Platyhelminthes			
Euvalentinia darwini (Cunningham)	K		0.8	Polycladida sp. 1		1.0	
Santia marmorata (Vanhoffen)	K	3.5	0.2	Polycladida sp. 2		0.3	
Uromunna dentata (Vanhoffen)	K	2.0	0.2	Nemertini			
Munna sp.		0.5		Indet. sp. 1		65.3	14.7
Tanaidacea				Indet. sp. 2			0.3
Apseudes antarcticus Beddard	M		0.2	Annelida			
Nototanais dimorphus (Beddard)	K,M	0.3		*?Eunoe* sp.		0.8	
Zeuxo phytalensis Sieg	M		0.2	*Polydorella* sp.			0.7
Zeuxoides pseudolitoralis Sieg	M	0.8	2.2	*?Proclea* sp.		0.5	
Mollusca				*Schistomeringos* sp.			12.3
Eatoniella caliginosa (Smith)	K	1005.8	14.3	Exogoninid sp.			0.5
Laevilittorina heardensis Dell		9.8	1.8	Phyllodocid sp.			0.2
Macquariella hamiltoni (Smith)	M	24.0	0.5	Polynoid sp.			0.2
Nacella maquariensis (Finlay)	M	0.3		Oligochaeta sp. 1			9.2
Omalogyra cf. *atomus* (Phillipi)		5.0	6.6	Hirudinea sp.		0.5	0.2
Skenella cf. *sinapi* (Watson)		1.8					
Laevilittorina sp.			0.2				

* In addition to described species listed here, *Limnoria carptora* Cookson, an isopod endemic to Heard Island, and *Nacella kerguelensis* (Smith) and *Pellilitorina setosa* (Smith), two gastropods also recorded from Kergüelen Island, were collected from *Durvillaea antarctica* holdfasts.
† Indicates whether the species is also recorded from Kerguelen Island (K) or Macquarie Island (M).
‡ Four clumps in lower intertidal zone.
§ Six clumps.

atomus and *Nacella kerguelensis*, have been recorded from *D. antarctica* holdfasts at both Heard and Kerguelen Islands, only *Hyale hirtipalma* from *D. antarctica* holdfasts at both Heard and Macquarie Islands, and only *Parawaldeckia kidderi* from *D. antarctica* holdfasts at both Kerguelen and Macquarie Islands. By comparison, nine invertebrate species have been recorded in *M. pyrifera* holdfasts at both Kerguelen and Macquarie Islands (Arnaud 1974, Edgar 1987).

The lack of similarity between *D. antarctica* holdfast faunas recorded at the different Subantarctic islands may nevertheless be attributable to small collections having been made at each island and the paucity of data on intra-island variation between sites. The only information on holdfast faunas at sites separated by distances exceeding several kilometres is provided for two sites at Macquarie Island (Smith & Simpson 1998), with the majority of abundant species present at the two sites. Additional collections from multiple sites around each island and collections of drifting plants are required to clarify unequivocally the biogeographic importance of *Durvillaea* and *Macrocystis* drift.

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TABLE 2
Abundance of invertebrate species collected from attached *Durvillaea antarctica* holdfasts at the beginning and conclusion of experiment

Taxon	Shore*								Tethered†							
	20 Nov 1987				21 Feb 1988				1 day				93 day‡		93 day control§	
Hyale hirtipalma	3	10	1	1	92	34					1	1		1	12	
Paramoera austrina f. kergueleni	1	1	2										38	34	55	23
Jassa sp.		1									2					
Probolisca ovata															1	
Limnoria carptora	4	97	36	56	492	11	6	79	4	1	1		3	3		2
Cassidinopsis emarginata		1														
Zeuxoides pseudolitoralis					5			1								
Collembola sp.	1				18		1	1								
Coleoptera sp.	1			1												
Acarina sp.3	6	1			34	2	3	10								
Laevilittorina heardensis		59	12		325	38	2	55	3	1	2	1	1	2		
Zalipais sp.		2														
Omalogyra cf. atomus	1															
Eatoniella caliginosa		14														
Nacella kerguelensis					3											
Pellilitorina setosa					5											
Capitella sp.		5	1													
Jasmineira sp.		35	5	2												
?Proclea sp.		1					1	1		1						
Oligochaeta sp. 2	1															
Oligochaeta sp. 1	4	21	16	8	63	16	4	63						2	5	
Polycladida sp. 3		2			37		1	1								
Polycladida sp. 4	1															

* Four replicates collected as faunal control on each occasion. † i.e. buoyed at sea for one and 93 days. ‡ Two lost to wave action.
§ Four defaunated by submergence in freshwater at the commencement of the study; two lost to wave action.

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COASTAL STUDIES AT HEARD ISLAND 1992/93: CHANGES IN SEA SURFACE TEMPERATURE AND COASTAL LANDFORMS

by Ken Green

(with one table and five text-figures)

GREEN, K., 2000 (30:vi): Coastal studies at Heard Island 1992/93: Changes in sea surface temperature and coastal landforms. *In* Banks, M.R. & Brown, M.J. (Eds): *HEARD ISLAND PAPERS. Pap. Proc. R. Soc. Tasm.* 133(2): 27–32. ISSN 0080–4703. Australian Institute of Alpine Studies, P0 Box 2228, Jindabyne, NSW, Australia 2627.

Sea temperature was measured weekly at Spit Bay, Heard Island, from April 1992 to March 1993. Temperatures were generally higher than those recorded in 1949 (at Atlas Cove), but these sites are not strictly comparable. Sea temperatures around Heard Island were stable from the 1920s to the 1940s, with a general increase in sea surface temperatures in the region being a recent phenomenon accompanied by widespread glacial retreat and the accelerated erosion of coastal features since the early 1950s. There is an area of active erosion by both water and wind in an arc from Winston Lagoon on the southeastern coast through to the northeastern coast at Compton Lagoon. This is most likely an effect of the loss of glaciers allowing strong erosive water movement along the coast. Movements of this dynamic coastline have important implications for long-term monitoring studies and for the management of the island.
Key Words: global warming, glaciers, erosion, Heard Island.

INTRODUCTION

Those researchers looking for evidence of, or a visible result of climate change on land look preferentially to glaciers. However, the retreat or mass diminution of glaciers also has a flow-on effect, the retreat of tidewater glaciers in particular altering coastal dynamics. Changes in coastal morphology at Heard Island (53°06'S, 73°32'E) have always been of greatest interest to those whose mode of transport on the island has been foot. Ledingham (1987), for example, included a map and accompanying text describing access by foot around the island in 1986/87. Most observed changes to the coast since human occupation of Heard Island have glacial retreat as their proximate cause, with climate warming as the ultimate cause (Allison & Keage 1986).

The impact of glacial retreat on the coastal morphology of the northwestern end of Heard Island has been negligible. Jacka Glacier, for example, prevented travel to Red Island from Atlas Cove in the early ANARE days (1947–54), but its retreat, while making travel possible by foot, has not altered the coastline of the Laurens Peninsula (fig. 1). The beach in front of the Vahsel Glacier was considered uncrossable in 1985, with ice falls and waves to the snout (Burton & Williams 1985), and was reported in the 1986/87 expedition to be passable at low tide but dangerous, due to large ice falls (Ledingham 1987). The 1987/88 expedition made several crossings at low tide (E.J. Woehler, pers. comm.). Such differences in opinion may be due more to the state of the tides than large-scale changes in the beach. A cursory examination of the coast of the northwestern end of Heard Island over a period of a month in early 1992 showed no great differences from the situation documented in 1987/88 by Kirkwood (1989a).

This paper is mainly concerned with the area of active erosion along the coastline of Heard Island in an arc from Winston Lagoon on the southeastern coast around to the northeastern coast at Compton Lagoon. Changes to the glaciers themselves have been dealt with by Allison & Keage (1986). Loss of mass in a glacier will not have an immediate impact upon rates of coastal erosion; hence, glacial retreat will only be covered insofar as it affects the coastal morphology. Therefore, this paper is concerned with evidence of warming in the Heard Island area and the impact this is having on the coastal morphology.

METHODS

Sea temperature was measured weekly at Spit Bay camp from April 1992 to March 1993. Water was collected in a plastic bucket from the sea within 1 m of the cobble beach. Temperature was measured in the morning to avoid any confounding effect of diurnal variation. The temperature was recorded to the nearest 0.1°C with a standard meteorological thermometer (Dobbie –20°C to +60°C). Sea temperatures taken from the RSV *Aurora Australis* at Spit Bay and in Atlas Cove on 23 January 1992 were compared. Temperatures taken from the shore of Spit Bay were compared with those taken from the MV *Icebird* on 11 and 12 March 1993, whilst it was anchored off Spit Bay.

Meteorological observations began at Spit Bay on 1 March with temporary housing for the instruments. The screen and raingauge were set up on 7 March and instruments zeroed at 0000 GMT the following morning, so official observations began on 9 March. Standard meteorological observations were made at 0000 GMT which was 0500 local Heard Island time.

Observations of coastal changes were obtained from photographs, previous expedition reports and direct observations in 1990 and 1992/93. Surface water was collected from Stephenson Lagoon and from the sea off Spit Bay in March 1993. Density values of these samples were determined with an Anton Paar DMA 55 density meter, with salinity values calculated after Whitfield & Jagner (1981).

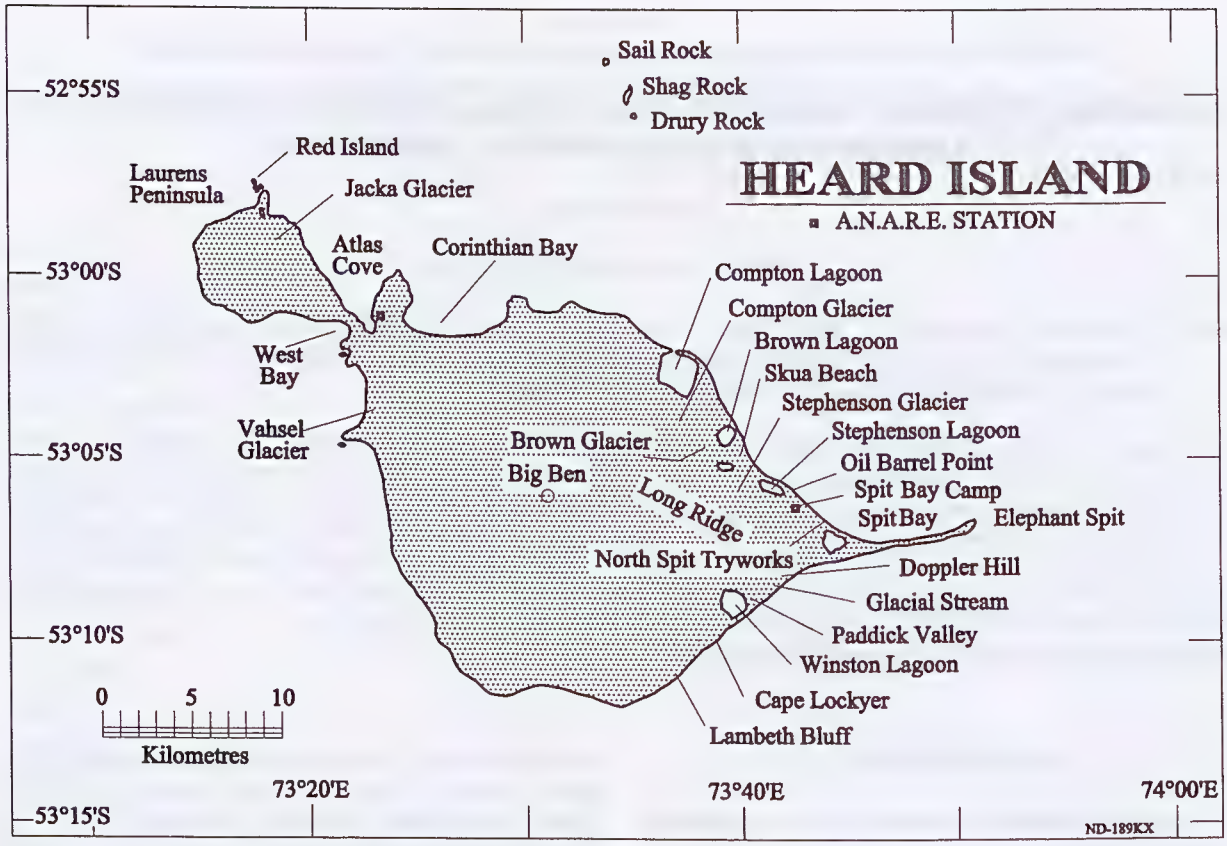

FIG.1 — Heard Island, showing places referred to in the text.

RESULTS AND DISCUSSION

Sea Surface Temperature

The Spit Bay site was not strictly comparable to that used by Ealey & Chittleborough (1956) in 1949 (their station II), which was about 400 m offshore over 9 m of water in the comparative calm of Atlas Cove. Temperatures recorded at Spit Bay in 1992/93 were similar to those given for Antarctic surface waters at the Antarctic Convergence in summer and winter respectively (Deacon 1933). By contrast, Ealey & Chittleborough (1956) found that air temperatures lowered the water temperature in 1949, with the effect being greater closer to shore. The relationship with conditions on shore, which are dependent upon the surrounding Antarctic water mass (Allison & Keage 1986), and how this relationship, in turn, affects the temperature of nearshore waters is difficult to unravel. However, the 3 .4°C recorded from the shore of Spit Bay on 8 March 1993 was similar to the 3.2°–3.4°C recorded from the MV *Icebird* off Spit Bay on 11 and 12 March 1993. Sea temperature at Spit Bay dropped by about 2°C from April to late June 1992 and then fluctuated around 1°C throughout the winter (reaching a low of 0.4°C on 19 October 1992) before rising from late November (fig. 2). Surface water temperatures recorded in Atlas Cove were generally lower in 1949 and fell to below zero, with sea ice recorded on two occasions (Ealey & Chittleborough 1956). The photograph in Ealey & Chittleborough (1956) showed that the ice was not just a skin on the water but quite robust pancake ice. Minimum temperatures at Atlas Cove in 1949 for 8/9 July and 2/3 August (the days before and during ice formation) were –8.9°/–8.9°C and –10.6°/–7.8°C respectively (Bureau of Meteorology 1953). Both the average maximum and the average minimum air temperatures over the period covered by Ealey & Chittleborough (1956) were lower than at Spit Bay in 1992/93. Air temperatures at Spit Bay in 1992 fell to a minimum of –7.2°C, with Stephenson Lagoon freezing to a depth of at least 0.5 m through the winter. However, unlike the waters of Atlas Cove in 1949, the calm saline waters of Compton Lagoon did not freeze in winter 1992. Temperatures recorded from the RSV *Aurora Australis* on 23 January 1992 were similar at Spit Bay at 1100 h (2.6°C) and at Atlas Cove at 1230 h (3.0°C). These factors together would indicate that, although the two sites are not strictly comparable, the higher sea temperatures recorded in 1992 compared with those in 1949 may well be indicative of a general warming of the

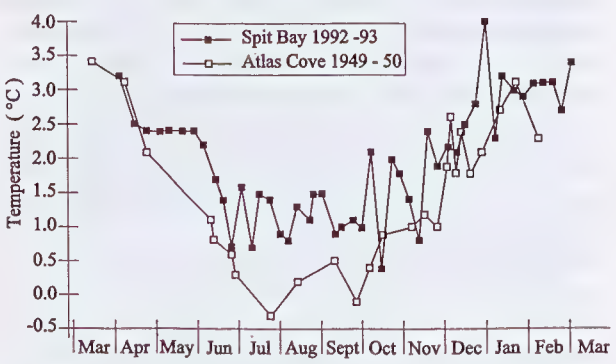

FIG. 2 — Sea surface temperature recorded at Spit Bay Camp in 1992/93 and at Atlas Cove in 1949/50.

TABLE 1
Monthly summary of meteorological data for Atlas Cove 1949–54 and Spit Bay 1992–93

Month	Mean maximum 1992/93	Mean maximum 1949/50	Range of mean maxima 1949–54	Mean minimum 1992/93	Mean minimum 1949/50	Range of mean minima 1949–54	Lowest minimum 1992/93	Lowest minimum 1949–50
Jan and Feb*	5.2			1.3			–0.5	
March	6.5	5.3	3.7 to 5.8	0.8	1.2	0.6 to 2.0	–1.5	–1.9
April	7.0	4.9	2.9 to 5.4	1.3	0.6	0.6 to 1.3	–0.5	–3.3
May	4.3	3.1	2.6 to 4.4	–0.4	–0.8	–0.8 to 0.9	–2.8	–5.5
June	4.4	0.7	0.6 to 2.7	–1.6	–3.8	–3.8 to –0.3	–4.5	–8.5
July	2.0	–0.5	–0.5 to 2.6	–2.3	–4.8	–4.8 to –0.8	–5.5	–9.1
August	2.0	0.4	0.4 to 2.7	–2.7	–3.8	–3.8 to –1.0	–6.5	–10.6
September	4.9	0.1	0.1 to 1.8	–2.5	–4.6	–4.6 to –2.3	–7.2	–8.8
October	4.0	1.2	0.9 to 2.2	–2.4	–2.5	–2.5 to –1.1	–6.0	–7.3
November	6.8	1.4	1.4 to 3.3	–0.1	–1.7	–1.7 to 0.0	–2.8	–3.5
December	6.7 (5.1)	3.6	3.6 to 4.4	1.1 (1.4)	0.3	0.3 to 0.9	–0.8	–1.8
January	6.6	5.0	4.7 to 5.5	1.3	1.2	1.1 to 1.9	–0.5	0.1
February	9.8	4.7	4.6 to 6.0	1.7	1.3	1.3 to 2.4	–1.5	–0.8
March†	6.9			0.6			0.3	
March to Feb	5.4			–0.5			–7.2	

* 23 days only at Atlas Cove
† Records taken for the first ten days of March 1993.

surface waters around Heard Island. The possibility that the temperature rise is due to volcanic activity is not borne out by the rise in temperature and retreat of glaciers at Iles Kerguelen, despite the lack of volcanic activity there (Allison & Keage 1986), and an explanation must be sought elsewhere.

The five-year mean zonally averaged data of Paltridge & Woodruff (1981) showed sea surface temperatures in the Heard Island region roughly constant from 1880 to the late 1920s but then increasing steadily to 1977. Temperatures recorded at Atlas Cove in November 1949 (1.0°–1.2°C) did not differ much from the 0.9° to 1.2°C taken in Corinthian Bay in November 1929 (Howard & Sverdrup 1940). There were no obvious changes in the glaciers between the 1874 *Challenger* expedition and the 1929 BANZAR expedition, with only minor recession to 1955 (Budd & Stephenson 1970). These data suggest that what temperature rises there have been have mainly occurred since the 1950s. The accompanying glacial recession (in horizontal extent and/or depth), occurring between 1947 and 1980, mainly took place since 1970, in response to an increase in atmospheric temperatures since the mid 1960s (Allison & Keage 1986). The significance and uniformity of trends of higher temperature in the South Polar and Southern Ocean regions is increasing as more data are collected (Jacka & Budd 1991), and so the effects of this warming might be expected to be observed at Heard Island for some time.

Meteorological Observations

A full summary of meteorological data collected by the 1992 wintering ANARE expedition is included in the expedition report (Green 1993a). Here, I concentrate on comparisons with the conditions during the sea surface temperature study of Ealey & Chittleborough (1956) (table 1). The mean maximum temperature of 5.4°C for the months for which data are complete (March 1992 to February 1993) was 1.6°C higher than for 1949, but the mean minimum (–0.5°C) was close to the average for the six-year period (1949–54). The lowest minimum (–7.2°C) was also close to the average of the lowest minima at Atlas Cove for the six-year period (1949–54). The highest maximum, however, the 21.6°C recorded in April 1993, was well above the highest for any year in the 1949–54 period, and on nine days spread across four months (April, June, September and February) the maximum recorded was higher than for the six-year period (1949–54). These temperatures all occurred on days when fohn winds blew and would have inflated the average maxima but, because temperatures were only taken once a day, unlike at Atlas Cove (where permanent observers took three-hourly recordings), average temperature figures cannot be obtained from our data. The lack of average temperature data, however, is compensated for by other studies. Jacka *et al.* (1984), for example, examined surface temperature data for islands in the Southern Ocean and reported a general warming over the past 40 years. Additionally, using data collected by an Automatic Weather Station at Atlas Cove (April 1980 to February 1983), Allison & Keage (1986) estimated a temperature increase at Heard Island similar to the 1.5°C recorded at Iles Kerguelen after 1964. The rate of warming at Heard Island is consistent with that expected from predictions of global warming due to the enhanced greenhouse effect (Jacka & Budd 1991).

Changes in Coastal Morphology 1987/88 to 1992/93

Lagoons in winter

There are four major pro-glacial lakes at the eastern end of Heard Island which can form a barrier to coastal movement on foot in summer but, except for Compton Lagoon, provided a rapid means of transport in winter 1992. Winston Lagoon had ice that would support a skier up to 100–200 m from the shore (fig. 3). Although the extent of the ice did not

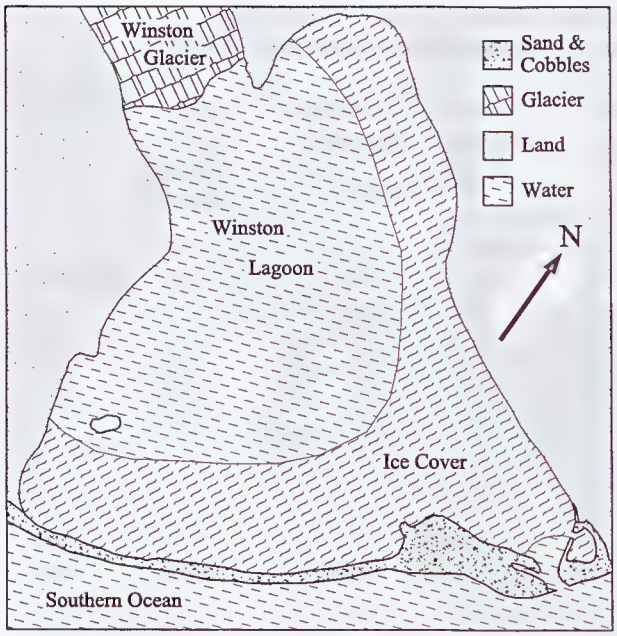

FIG. 3 — Extent of ice on Winston Lagoon, 23 July 1992. Length of N arrow represents 0.5 km.

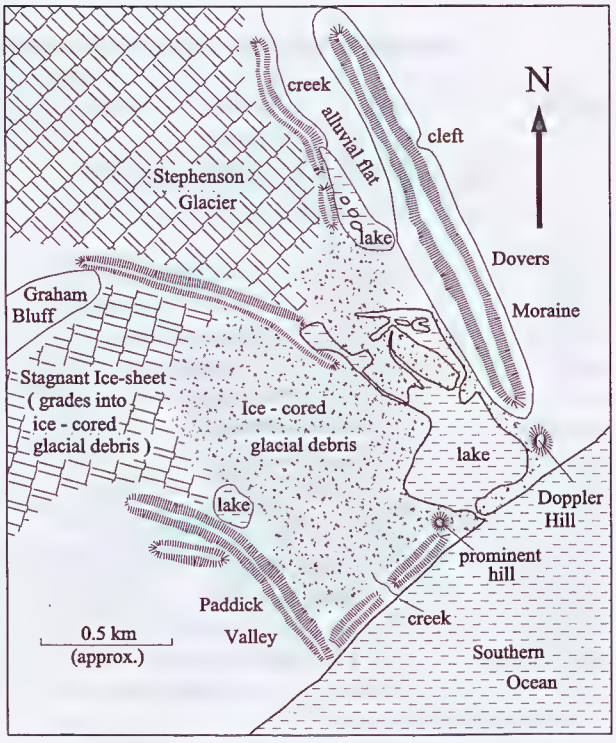

FIG. 4 — Extent of pro-glacial lake feeding Glacial Stream, 1992.

increase markedly from that mapped, it later expanded in the southwestern corner of the lagoon, allowing access to the small island located there. The pro-glacial lake forming behind Glacial Stream (see below) could be crossed on ice for much of the winter, but increased salinity made the ice softer and less safe for travel as winter progressed. The freshwater Stephenson Lagoon was frozen through winter 1992, except at the outlet and at the foot of the ice cliffs of Stephenson Glacier. Stephenson Lagoon had the deepest measured ice of the pro-glacial lakes. Brown Lagoon froze from the sea to the snout of Brown Glacier in 1992 with solid ice throughout, but ice thickness was not measured.

Southeastern coast

There was continued erosion, both by water and wind, of the southeastern coast of Heard Island through 1992. There is a large input of sediment from high-erosion areas such as that from Cape Lockyer to Lambeth Bluff. Erosion on the southeastern coast was most noticeable at the westernmost moraine of Paddick Valley (as also reported by Kirkwood 1989b) and along the moraine and beach between Paddick Valley and Doppler Hill. A number of agents were responsible, including wave action, wind, erosion through snow movement or water runoff. Allison & Keage (1986) commented on the widening of beaches east of Cape Lockyer. This widening was sporadic, and at one stage, in 1992/93, it was possible to walk around Cape Lockyer on a temporary beach. Additionally, the beach below Doppler Hill was extended outwards during the southern elephant seal *(Mirounga leonina)* breeding season of 1992/93. The southeastern coast is the major source of material for aeolian deposits on the Spit. This deposition is particularly evident during the southern elephant seal breeding season, when harems act in a similar fashion to snow fences, trapping enormous quantities of sand, so that the harem may rise up to a metre above the surrounding beach.

Glacial Stream

There have been a number of changes to both Glacial Stream and the pro-glacial lake formed behind it. The outlet has been considerably widened since 1987 (much of this widening occurred before the ANARE expedition of 1990), and the pro-glacial lake was larger in 1992/93 than in 1987/88 (fig. 4). The stream and pro-glacial lake became tidal in 1992, turning the water brackish when the outlet was deepened sufficiently to allow the high tide to return against the flow of freshwater. Intense erosion and longshore drift along the southeastern coast with deposition in the Glacial Stream outlet in 1992/93 at times re-formed the sandbar and prevented the influx of seawater.

Elephant Spit to Spit Bay Camp

Elephant Spit was complete from early in 1992 through to September, when it was again broached. The resulting island was separated from the Spit by shallows as late as February 1993 when a crossing could be maddû Observations from Long Ridge in 1992 suggested that the spit had curved to the north since 1990.

The coast from Elephant Spit to Spit Bay Camp is subject to intense erosion, although the extent can only be determined at a few places. Kirkwood (1989a) reported the North Spit tryworks to be about 30 m inland in 1987/88. Green (1990) reported "extensive beach erosion" at the tryworks, and photographs taken at that time show the tryworks to be about 10 m inland of a 3 m high sea-cut cliff. During 1992, parts of the cliff fell away, and the tryworks was only 3 m from the sea-cut cliff by the time the expedition departed in March 1993. Little erosion occurred at Oil Barrel Point between 1987/88 and 1992/93, but the sea made inroads immediately west of the barrels. The coast from there to at least the creek outflow near Spit Camp was severely eroded by 1992/93. This was evidenced by the cutting back of the soft, pale sediment cliff to the west of Oil Barrel Point, the exposure of further sealers' artefacts and the continued undercutting of the refuge hut

at Spit Camp. It was recognised in 1986 that coastal erosion threatened this hut (Kirkwood 1989b); it disappeared after the departure of the 1992 wintering expedition (S. Reeve, pers. comm.).

Photographs taken during the erection of the refuge hut at Spit Bay show the seaward extent of the Stephenson Glacier, which provided a breakwater protecting the shore from the strong southeasterly water movement along the coast. The strength of this longshore drift was demonstrated in 1992 by the movement of a concrete block (consisting of a bag of concrete that became soaked accidentally) 60 m to the east of the refuge hut. The retreat of this glacier and Brown Glacier is probably the main cause of the accelerated erosion on this coast, while the reduction in sediment input due to the retreat of glaciers is of secondary importance.

Stephenson Lagoon

Stephenson Lagoon was fresh water with a short, winding stream to the sea on arrival of the 1992 ANARE expedition. Winter storms deepened and straightened the outlet and removed one of the three remaining ridges of moraine debris (remnants of the terminal moraine that made up the spit between lagoon and sea). Breaches in Stephenson Spit sufficient to make crossing difficult were predicted by Kirkwood (1989b) and, by the end of the summer of 1992/93, crossings were prevented by waves breaking into the outlet. Surface-water samples collected from Stephenson Lagoon and from the sea off Spit Bay in March 1993 had salinity values of 17.9 parts per thousand (ppt) and 26.7 ppt respectively. This indicates a considerable mixing of seawater with the lagoon, especially when considering the amount of runoff from the glacier, due to the thaw. The tidal nature of Stephenson Lagoon has had some interesting effects and will lead to further changes.

(1) Marine organisms were common in Compton Lagoon and should become more common in Stephenson Lagoon, should the tidal ingress continue. Amphipods were observed in Stephenson Lagoon after the spit was broached in 1993.

(2) The lagoon may not freeze in future, adding to the difficulties of winter foot transport.

(3) Green (1993b) suggested that the tidal nature of Stephenson Lagoon might lead to the more rapid retreat of Stephenson Glacier. This retreat has, in fact occurred, with oblique photographs taken in 1997 (K. Kiernan, pers. comm.) showing a substantial retreat of this glacier, possibly "due to melting by seawater and mechanical fracture following undercutting by tidal ... action" (Allison & Keage 1986). The land on the eastern side of Stephenson Glacier is very low lying (and may in fact be below sea level beneath the ice). Unless sufficient material is deposited, a channel could be created between Stephenson Lagoon and Glacial Stream. Already by 1992 there was an extensive pro-glacial lake to the immediate east of Stephenson Glacier between these two water bodies.

The northeastern beaches

The balance on this coast between deposition and erosion has been complex following the retreat of the Compton Glacier, with accumulation in places (such as the spit across Brown Lagoon) and erosion in others (Kirkwood 1989b). There are few fixed points at which erosion rates can be determined along this coast. There appeared to be little erosion on Fairchild Beach, but Skua Beach had changed markedly between 1987/88 and 1992/93. Kirkwood (1989b) had already documented the destruction of sealers' relics, and this continued in 1992. The sea frontage at the tryworks was gradually eaten away in a number of storms in 1992, so that the trypots, inland in 1987, were slowly undermined, with the outermost falling on the beach in December 1992 and disappearing in early 1993. The spit across Brown Lagoon was not broken in 1992/93 and appeared to be one of the more stable sections.

Compton Lagoon

The satellite image map with coverage of Compton Glacier for 9 September 1988 shows clearly the retreat of the glacier. This was a large ice front on the December 1985 edition of the Natmap *HEARD ISLAND* 1:50 000 map (based on the 1948 ANARE survey with additional information to 1963) and the changes to 1987/88 were mapped by Kirkwood (1989b). In 1980 the spit had a single breach, which had widened by 1987/88 with the addition of two further breaches (Kirkwood 1989b). The 1992/93 ice front is shown in figure 5.

CONCLUSION

The status of the Heard Island coastline was documented in detail up to the summer of 1987/88 by Kirkwood (1989a). Kirkwood's account concluded with speculation, as to further modifications to the Heard Island coastline. These included:

(1) Compton Spit disappearing and the lagoon becoming more bay-like;

(2) a reduction in width of Fairchild Beach;

(3) the opening of a breach in Brown Spit;

(4) a reduction in width of Skua Beach;

(5) the opening of a breach in Stephenson Spit resulting in it becoming tidal (as an additional speculation, connection of Stephenson Lagoon with the pro-glacial lake feeding Glacial Stream); and

(6) the loss of Oil-Barrel Point, North Spit Tryworks and the refuge hut at Spit Bay.

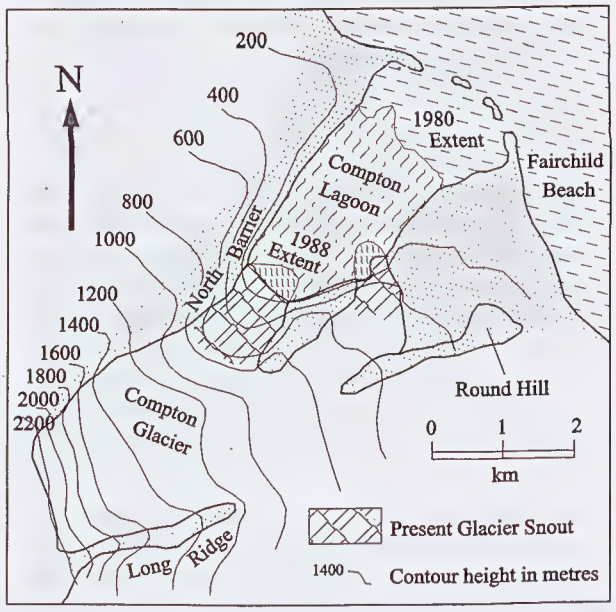

FIG. 5 — Retreat of the Compton Glacier, showing the extent in 1980, 1988 and 1993.

It is a measure of the dynamism of the current erosion regime on Heard Island that nearly all of these predictions came true within five years of the 1987/88 expedition. This has important ramifications for a number of long-term monitoring or management programmes on the island, not the least of which are the monitoring of penguin and seal numbers (already made difficult by changes in the Spit) and the documentation and conservation of sealers' sites.

Heard Island remains one of our best sites for examining the reality and impacts of climate change but, apart from the period 1947–1954 and 1992/93, there are few climatic data. A remote weather station was erected at Atlas Cove in 1986 but collected data for less than two months. To obtain good quality data, a buoy moored permanently at one of the 1949 locations may be necessary to record sea surface temperature, together with a functioning remote weather station at Atlas Cove. These two would form the basis of a valuable data set. However, they would require a commitment to more regular trips to Heard Island.

ACKNOWLEDGEMENTS

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(accepted 5 July 1999)

TERRESTRIAL VEGETATION AND ENVIRONMENTS ON HEARD ISLAND

by D.M. Bergstrom and P.M. Selkirk

(with three tables, one text-figure, one plate and an appendix)

BERGSTROM, D.M. & SELKIRK, P.M., 2000 (30:vi): Terrestrial vegetation and environments on Heard Island. *In* Banks, M.R. & Brown, M.J. (Eds): *HEARD ISLAND PAPERS. Pap. Proc. R. Soc. Tasm.* 133(2): 33–46. ISSN 0080–4703. Department of Botany, The University of Queensland, Brisbane, Queensland, Australia 4072 (DMB); and Department of Biological Sciences, Macquarie University, Sydney, New South Wales, Australia 2019 (PMS).

Significantly ice-covered and with a very small flora (11 vascular species and about 60 bryophyte taxa), Heard Island is still emerging from the effects of the last glacial maximum. This study presents the results of a general vegetation survey. A baseline framework of environmental conditions that affect vegetation on the island is described and a classification (TWINSPAN) analysis based on presence/absence data of both vascular plant species and bryophyte taxa is provided. Distinct suites of taxa were identified on the island, some containing bryophytes only. Fifteen ecological groups were delineated. A discussion of ecological amplitude of important bryophyte and vascular plant taxa on Heard Island is included.

Key Words: Subantarctic, tundra, vegetation, bryophytes, cushion plants, Heard Island.

INTRODUCTION

Subantarctic Heard Island (53°06'S, 73°32'E) is approximately 4850 km southeast of southern Africa, 4350 km southwest of Western Australia and 1650 km north of the Antarctic continent. It is an emergent portion of a mid-oceanic ridge with a mixed geology of pelagic limestones and volcanics (Clarke *et al.* 1983), with a large active volcano (Big Ben — 2750 m) dominating the landscape. The island is 44 km long on a WNW–ESE axis.

Heard Island has a history of glaciation from the Miocene (Quilty *et al.* 1983), with many glaciation events associated with cooling episodes in the Pleistocene. Severely glaciated today, it is essentially still emerging from the last glacial maximum approximately 18 000 years ago (Climap 1976). Allison & Keage (1986) estimated that, in 1980, approximately 80% of Heard Island was ice-covered, with glaciers descending from 2400 m to sea-level. Ice-free areas lie, in general, along the coastline and rarely extend above 400 m a.s.l. As glaciers isolate these ice-free areas, each can be considered analogous to an individual island and Heard Island analogous to an archipelago (Bergstrom & Selkirk 1997). Glacial retreat is occurring rapidly with current climate warming (Scott 1990), with some ice-free areas coalescing.

Heard Island has a remarkably equable temperature regime both diurnally and annually, moderated largely by the surrounding ocean. Weather station data collected between 1948 and 1958 recorded a mean annual temperature of 1.2°C, with a seasonal range of 4.5°C. Snow or rain falls on most days of the year, and the island is severely ravaged by wind storms, mostly from the northwest to southwest quadrants (Allison & Keage 1986).

About 5% or 20 km^2 of the total surface area of Heard Island is covered by substantial vegetation. Low-growing, herbaceous flowering plants and bryophytes are the major plant components. Only 11 flowering plant species and 58 bryophyte species have been recorded from the island (Scott 1989, Bergstrom & Seppelt 1988, Bergstrom & Selkirk 1997). A different and perhaps more extensive vegetation, described as a low scrubby fernbush, existed on the island during the Tertiary and included a variety of ferns and a podocarp (Quilty *et al.* 1983).

There have been few studies of terrestrial plant ecology on Heard Island. Jenkin (1980) briefly described five vascular plant communities on Heard Island. In a preliminary study, Hughes (1987) expanded this to six. These communities are visually recognisable though subjective, and are based on physiognomic, microtopographic and some floristic features. Scott defined six mappable vegetation units based on Hughes' (1987) scheme and provided more detailed descriptions of the vascular plant communities. A summary of the six vascular plant communities follows.

(1) "*Poa cookii* maritime grassland" is characteristic of nutrient-enriched, animal influenced environments (Hughes 1987, Scott 1988). This community is dominated by the small tussock grass *Poa cookii* (Hughes 1987), with the nitrophiles *Callitriche antarctica* and *Montia fontana* also common.

(2) "Pool complex" occurs in areas where drainage is impeded. *Callitriche antarctica* is the indicator species (Hughes 1987, Whinam 1989). Whinam (1989) delineated eight ecological groups within this community depending on extent of cover by *Azorella selago* and a mixture of other species. Areas which can be categorised as pool complex vegetation most often occur inland of a narrow fringe of maritime grassland on coastal flats. These areas are subjected to seasonal disturbance by wallowing and moulting elephant seals and fur seals.

(3) "Meadow community" category encompasses vegetation dominated by either of two grass species: *Poa cookii* or, at some sites at the eastern end of the island, *Deschampsia antarctica.* Such communities are reported from environments where the water table is close to the surface. Usually bryophytes are common, as are the vascular plants *Montia fontana, Acaena magellanica* and *Callitriche antarctica* (Scott 1988).

(4) "Herbfield" is dominated by either of two herb species: *Pringlea antiscorbutica* or *Acaena magellanica* (Hughes 1987, Scott 1988). *Acaena magellanica* has only been recorded from the eastern end of the island (Scott 1988). Herbfield has been reported from a variety of situations such as sheltered moraine slopes and gullies. Stands can be mono-

specific or mixed, with *Azorella selago* and *Poa cookii* being a subsidiary species. *Pringlea antiscorbutica* can colonise scree slopes, landslip surfaces and recently deposited moraines. It is also common along gravelly stream margins (Hughes 1987, Scott 1988).

(5) "Cushion carpet vegetation" is dominated by *Azorella selago*. In this vegetation category, individual cushions of *A. selago* coalesce into continuous carpets. Hughes (1987) described cushion carpet communities occurring in locations of moderate to high wind exposure. This type of vegetation is the most widespread on Heard Island, occurring throughout the altitudinal range of vegetation. Scott (1988) recognised five subcategories: "dense cushion carpet", "patchy cushion carpet", "*Azorella/Poa cookii* network vegetation", "*Azorella* mossfields" and vegetated cliff edges and ledges. "Dense cushion carpet" is almost completely dominated by *A. selago* with sporadic occurrence of *Poa cookii, P. kerguelensis, Colobanthus kerguelensis* and bryophytes. "Dense cushion carpet" grades to "patchy cushion carpet". "*Azorella/Poa cookii* network vegetation" occurs in dense cushion carpet on a variety of slopes, and from a distance presents a network appearance. "*Azorella* mossfield" vegetation consists of dense carpets of bryophytes between *A. selago* cushions.

(6) "Feldmark communities" are characterised by less than 50% vegetation cover. Hughes (1987) described feldmark as having high relative vascular plant diversity but low species abundance, with predominant plants being *Azorella selago, Poa kerguelensis, Colobanthus kerguelensis, Pringlea antiscorbutica*, bryophytes and lichens. Scott (1988) recorded feldmark on well-drained areas of high altitude/high wind exposure, areas of recent glacial retreat, flat valleys likely to be subject to cold air drainage, and geologically recent lava flows.

This paper documents a general vegetation survey conducted on Heard Island during the 1986/87 ANARE expedition. First, a framework of environmental conditions that affect vegetation on the island is set. Second, the results of a classification (TWINSPAN) analysis are presented. In particular, this analysis emphasises the diversity of bryophyte taxa within common vegetation types and landscape units on the island. The previous plant community studies described above focused on the vascular plant component, generally amalgamating all bryophytes into a single taxon "bryophytes" (Hughes 1987, Whinam 1989) or a small number of collective groups (Scott 1990). Total bryophyte cover is a useful measure, but information on plant community complexity and species richness is not gathered. Considering that on Heard Island there are five times as many bryophyte taxa (53) as vascular taxa (11) (Bergstrom & Seppelt 1988, Bergstrom & Selkirk 1997), the loss of information consequently is large. Finally a discussion of ecological amplitude of important bryophyte and vascular plant taxa on Heard Island is presented.

ENVIRONMENTAL COMPONENTS THAT AFFECT HEARD ISLAND PLANTS AND PLANT COMMUNITIES

In this section, major environmental components that are significant to plants and plant communities are identified and their variation on the island described. Most have yet to be described quantitatively. They are listed here with a view to future studies on Heard Island.

Animal-derived Nutrients

In identifying patterns of variation in the climates, soils and vegetation on some Subantarctic islands, Smith & French (1988) recognised changes in soil chemistry, caused by manuring by seals and seabirds, as a major component affecting vegetation. Heard Island was not considered in their study, but animal-derived nutrients are of major importance there. A nutrient gradient is apparent, diminishing away from coastal seal and bird-breeding, resting and hauling-out areas. Areas affected by direct manuring by seals, penguins, cormorants and giant petrels are generally devoid of vegetation, reflecting toxic nutrient levels and physical damage to plants. In some areas, such as the periphery of a Gentoo penguin rookery inland of Spit Bay hut, scorching of plants by guano was evident.

Volatilisation of ammonia from penguin rookeries and subsequent deposition on vegetation downwind has been reported both on Macquarie Island (Jenkin 1975, Erskine *et al.* 1998) and on Marion Island (Lindebloom *in* Gremmen 1982). Areas adjacent to penguin and giant petrel rookeries support lush growth of *Poa cookii*, blue-green in colour, indicative of high nitrogen levels.

Direct small-scale nutrient input in the vegetation associated with burrowing petrel nests is likely to be of significance. Scott (1988) reported petrel nests in most vegetation types on Heard Island.

Dissolved Nutrients from Parent Rock

The influence of dissolved nutrients from parent rock on plants has yet to be determined. Most lavas on Heard Island are alkali basalts (Australian Antarctic Division 1995), as are the lavas on Marion (Verwoerd 1971). However, in an extensive plant ecological study on Marion Island, Gremmen (1982) recorded most sites having acidic pH levels. Unusually high levels of titanium and related elements have been reported from lavas on Mt Dixon, Laurens Peninsula (Australian Antarctic Division 1995).

Limestone deposits occur at various localities on the island (Quilty *et al.* 1983). There appears to be no distinct suite of limestone plant species. Quadrats surveyed on limestone moraines at the base of Anzac Peak, Laurens Peninsula, had similar bryophyte species composition to lava sites in the same area (see TWINSPAN Group 2, appendix). In Eastern Australia, basalt and limestone areas in the Blue Mountains have similar bryofloral components (A. J. Downing, pers. comm.).

Sea-salts

Deposition of sea-salts on Subantarctic islands can occur in a number of ways. In heavy storms, waves can splash directly onto coastal margins such as lava cliffs. Airborne sea-spray can be incorporated into winds blowing over land- and air-borne sea-salt particles can be "scavenged" from the atmosphere and deposited on land in precipitation (Mallis 1988). On other Subantarctic islands, deposition gradients appear to be related to the direction of the prevailing wind and settling mist (Mallis 1988, Smith 1987).

Similar patterns are evident on Heard Island. Halophytes, such as the moss *Muelleriella crassifolia* subsp. *acuta*, occur some distance inland on the south and southwestern sides

of the Laurens Peninsula and in the Long Beach region (regions that receive the brunt of the prevailing winds), but can only be found on beach-side rocks in the more sheltered Spit Bay region.

Water Availability

Many factors contribute to the variation in availability of water on the island. Although snow or rain falls on most days, local precipitation varies. Expeditions have reported that the eastern ice-free areas, such as the Spit Bay region, may have a generally less severe climate than on the north-western and southern sides of the island, with reduced cloud cover and precipitation. The controlling factor appears to be forced uplift of westerly or southwesterly moist air bodies over Big Ben (Ledingham 1987).

Extensive snow cover in winter provides spring meltwater, varying with local topography. Topographic depressions can allow accumulation of snow or ice which, on melting, provides free water for local vegetation. Scott (1988) reported meadow vascular plant communities in areas below late-lying snow banks.

Another major input of water is meltwater from glaciers (which feed creeks and outwash lakes) and from ice-cored moraines (permafrost) such as in areas of Dovers Moraine, in the Spit Bay region, where ice lenses extend into peats. In summer, in some areas, constant subsurface lateral water flow is available to deep-rooted plants such as *Azorella selago*.

Loss of moisture from terrestrial environments on the island is mainly influenced by evaporation rates and drainage rates. Most areas are subjected to strong, drying winds at some time. Very exposed areas could be described as wind deserts, with any precipitation being blown away or rapidly evaporated. In such areas, wind-driven mist may be the only source of moisture, making the environments suitable for ectohydric bryophytes but not endohydric vascular plants.

Drainage rates vary considerably on Heard Island. A large proportion of ice-free moraine, clinker lava and aeolian areas are free draining, but drainage rates are reduced in some areas. Solid beds or smooth lava (pahoehoe lava), such as near the ANARE base, can present a non-porous bedrock surface. Weathering in some areas, such as on the moraines directly behind Manning Lagoon (Long Beach region) or on the lavas near the alluvial flats, south of Anzac Peak (Laurens Peninsula), has yielded clay particles which increase the water-holding capacity of the substrate, as does accumulation of peat. There are a few areas of saturated peats on Heard Island, such as near the creekline draining into Sydney Cove on the Laurens Peninsula, and moraines directly behind Manning Lagoon in the Long Beach region.

In areas of impeded drainage, small pools or tarns occur, fed by local catchment areas. Pools at elevations above coastal plains are generally oriented parallel to lava ridges (Whinam 1989), suggesting topographic control of pool formation. On coastal plains and beach terraces, animal activity, in particular seal wallowing, contributes to reduced drainage (Whinam 1989).

Substrate Depth

Substrate depth and, hence, volume available for vascular plant root systems varies considerably in ice-free areas. Large areas of solid lava are either bare or thinly covered with cryptogamically derived peat. In rocky areas, such as clinker lava flows and scoria cones (pl. 1A, see p. 41), wind-blown sediment accumulates between rocks. Deep (> 0.5 m) unconsolidated substrates can generally be found on moraines, talus slopes, aeolian deposits and beach terraces. Peat deposits, derived mainly from *Azorella selago*, up to 2 m deep were measured on moraines in the Spit Bay region.

Particle Abrasion

Abrasion of plants by windblown particles, including sand, ash, snow and ice, is a major environmental disturbance on Heard Island. Ventifacts are evident in many exposed areas, such as along the Spit.

Surface Movement

Surface movement in ice-free areas on Heard Island can cause considerable reworking of the land surface and will affect dynamics of colonisation by plants here as on Macquarie Island (Bergstrom & Selkirk 1999).

Downslope movement occurs on unstable moraine slopes, talus slopes and scoria cone slopes. Frost-heaving, frost-raking and nubbin formation were observed between cushions of *Azorella selago* on moraine sediments. Sorted stripes occur on scoria and ash/sand sediments at the northern base of Mt Dixon. On the limestone moraines at the southern base of Anzac Peak, there were stone polygons up to 8 m in diameter.

Fluvioglacial activity is modifying terrestrial plant habitats on Heard Island. Entrapment of sediment in coastal glacial lagoons, redeposition and beach formation is generating new surfaces that can be colonised by terrestrial plants.

Although moraine surface material provides some insulation, ice-core melting occurs in midsummer. Slumping of surface material and burial of bryophyte vegetation was observed in 1987 in the higher areas (above 60 m a.s.l.) of Dovers Moraine, to the east of King Creek.

Biotic Interactions

Vertebrate animals disturb ground by trampling as well as adding nutrients. Scott (1988) described habitats used by seals and seabirds. Whinam (1989) described intensive use of coastal vegetation by penguins and seals and reported destruction of *Poa cookii* tussocks by giant petrels.

On Marion Island, herbivory is insignificant. Most energy flow and nutrient cycling occurs through the detritus level. The main mediators for nutrient mineralisation are soil macro-invertebrates (Smith & Steenkamp 1990). Such macro-invertebrates are also found on Heard Island and are likely to play a similar role.

General Climate Characteristics

Temperature gradients on the island appear to affect plant physiology. Phenological stages in vascular plants appear to be influenced by the milder climatic condition of the eastern areas compared with the northwestern and southern areas. In early December 1986 at Atlas Cove, *Pringlea antiscorbutica* and *Azorella selago* plants had flowerbuds within the rosette and cushion respectively. *Poa cookii* was in flower, but stamens were not mature. Plants growing in the Spit Bay region at the same time were advanced by at least two weeks in development. *Azorella selago* flowers were open, *Pringlea antiscorbutica* flowerheads were well elevated above the rosette and *Poa cookii* stamens had emerged with ripe pollen.

Table 1 lists major influences on present Heard Island vegetation and categorises them as "stress" or "disturbance" in the sense of Grime (1979). It is clear, however, that stress and disturbance are interlinked, since disturbance creates stresses for plants, and at times the categories are difficult to separate clearly.

Environmental components such as nutrients can have diametrically opposite effects, depending on their availability. For example, lack of nutrients can inhibit plant growth, excess nutrients can be toxic. A subjective scale is presented in table 1.

VEGETATION SURVEY AND CLASSIFICATION ANALYSIS

Methods

The basis of this study is a vegetation survey conducted on Heard Island during the 1986/87 Australian National Antarctic Research Expedition (ANARE). A stratified random sampling approach was adopted in selecting field sites. A total of 475, 1x1 m quadrats were surveyed during the eight-week field period. Sites were chosen to cover as many visibly distinct vegetation types as possible. Most quadrats (400) were either part of ten random quadrats in a series of 10 x 10 m areas, sampling recognisable landscape units/vegetation types, or were components of transects over distinct landscape features (such as creeks). The remaining samples were isolated quadrats.

In each quadrat the following habitat characteristics were noted:

- location;
- geomorphological description (moraine, clinker lava, lava flow or sand) and general notes on topography.
- altitude;
- general slope of the quadrat (although in clinker lava sites such values are meaningless, due to the irregularity of these sites);.
- aspect;
- unconsolidated substrate depth up to 100 cm depth measured using a 1 cm diameter metal probe;
- availability of water, rated on a subjective five-point exponential scale ranging from 1 (very dry) to 5 (surface free water);.
- exposure to wind, rated on a subjective five-point scale ranging from 1 (very protected) to 5 (very exposed);
- availability of light, rated on a subjective five-point scale ranging from 1 (exposed to full light conditions) to 5 (deep shade).

In each quadrat, cover values using the Braun-Blanquet (1932) scale were recorded for all vascular plants, bryophytes (as a collective unit), bare ground and rock. Braun-Blanquet cover values (+ to 5) were transposed to a scale, 1 to 6, to facilitate numerical analysis. Notes on individual cover values for major bryophyte taxa were also taken. Small samples of all bryophyte taxa were collected from each quadrat for identification in Australia.

Working in such a remote locality as Heard Island presents inherent logistic difficulties. Available field time was short. Transport between ice-free areas was by helicopter, commonly grounded by unfavourable weather. Access within major ice-free areas was generally by foot over difficult terrain. It was necessary to conduct fieldwork opportunistically: a consequence of this is uneven sampling. We were fortunate to have the opportunity to conduct fieldwork in three major ice-free areas on the island: the northwest areas encompassing the Laurens Peninsula, the Azorella Peninsula and Mt Drygalski; the eastern Spit Bay area; and the southern Long Beach area. Time spent in each of these areas was, however, uneven, and this is reflected in the number of quadrats collected from each (table 2).

Data was classified using TWINSPAN (Hill 1979), a polythetic divisive method of ordination and classification. The analysis constructs an ordered two-way table of taxa and sites by identification of differential (discriminating) species. Sites are classified first and taxa second, using the site classification as a basis. Levels of division are determined by the coherence of the ecological groups obtained. An "indicator" ordination is performed, in which highly preferential taxa or "indicator taxa" within ecological groupings are identified and ranked.

A preliminary analysis of the vegetation survey data set was performed using the Braun-Blanquet cover values for all the vascular species recorded and total bryophyte cover. Assignment of cover values for individual bryophyte taxa was not possible as field identification of such plants is not reliable; laboratory study has been necessary for accurate identification. The dendrogram generated for this analysis was compared with another analysis in which only presence/absence data were used, but included information on individual bryophyte taxa. A comparison showed that there was no significant change in the overall position of the vascular plant taxa in the dendrogram with reduction from cover values to presence/absence data. A TWINSPAN analysis of the data set using presence/ absence data only is presented here.

Results and Discussion

Figure 1 presents the dendrogram of the taxon classification. Fifteen taxon clusters (a–o) were identified, indicating distinct suites of plant species on Heard Island. In particular, there are distinct suites of bryophyte taxa that commonly occur together, with nine of the 15 clusters containing bryophytes only. The primary split in the data accounted for 68% of the variance in the data.

As well as 15 taxon clusters, 15 ecological groups (Groups 1–15) were delineated in the TWINSPAN analysis of the 475 quadrats. These groups contain between 13 and 67 quadrats. The frequency of occurrence of taxa in each of these 15 groups is shown in table 3. The TWINSPAN taxon clusters of figure 1 are maintained in this table.

TABLE 1
Summary of some of the major influences that affect plants on Heard Island

	+		0		–
Stress — restricts photosynthetic production* †					
Animal derived nutrients	Seal and sea-bird areas	Adjacent to seal and seabird areas	Burrowing bird nests	Skua pools	Inland, high altitude
Sea salt	Coastal	Northern and southern		Eastern	Inland
Water availability	Pools and lakes	Seepage zones, meltwaters, edge of pools	Protected gullies, lava areas with clay soils	Most ice-free areas, free-draining lava and moraine	Wind deserts
Substrate depth		Peat deposits on moraine	Moraine talus slopes aeolian slopes	Rocky areas	Solid lava
Temperature	*high* sheltered areas		0		*low* Cold drainage areas
Disturbance — partial or total destruction of biomass* ‡	*protected*		0		*disturbed*
Particle abrasion	Sheltered gullies, rocky hummocks				Exposed areas, aeolian deserts, rocky ridges
Surface movement	*protected* Flat areas, bed rock		0 Mild slopes		*disturbed* Cryoturbatic areas, steep slopes, talus slopes
Animal disturbance	*protected* Inland, high altitude	0 Burrowing birds nests		Adjacent to seals and seabird areas	*disturbed* Seal and bird areas

* 0 = midline (parameter perhaps being termed abundant). † + and – = extremities.
‡ subjective scale ranging from protected to disturbed.

TABLE 2
Number of quadrats surveyed in each major ice-free area of Heard Island

Area	Quadrat no.
Laurens Peninsula	119
Azorella Peninsula	40
Mt Drygalski	10
Spit Bay	250
Long Beach	45
Other areas	11

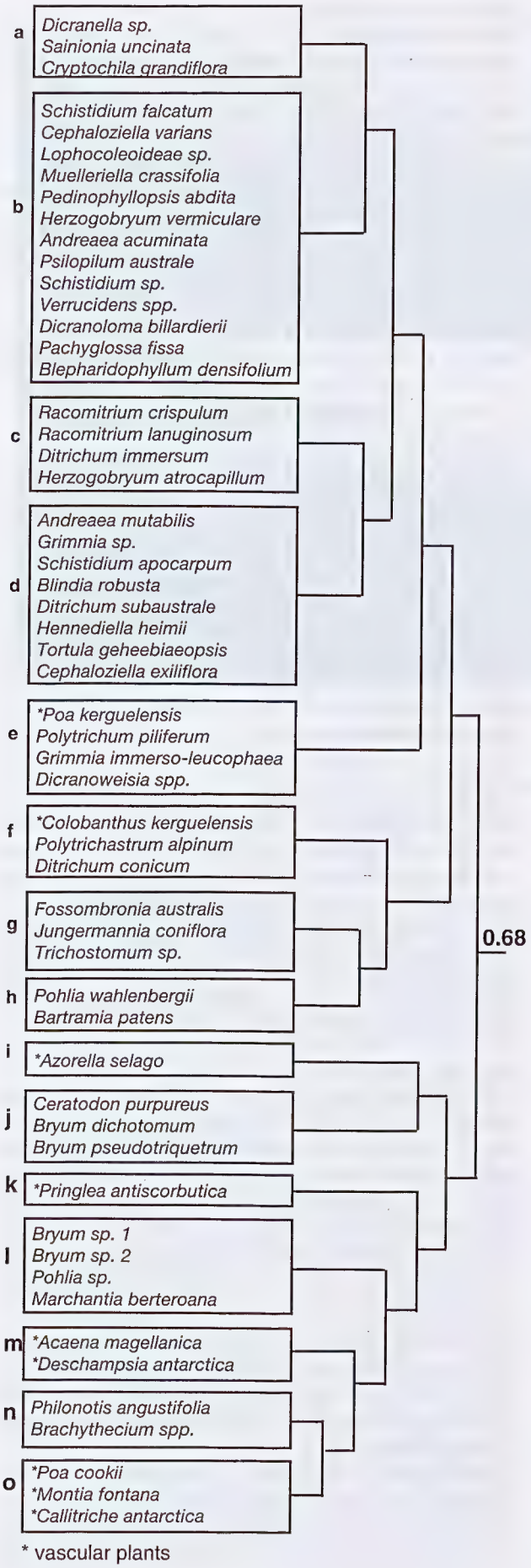
The cushion plant, *Azorella selago*, stands isolated in figure 1. This is of interest and relates to two aspects of the ecology and distribution of *A. selago* on the island. Firstly, *A. selago* is the largest and most dominant plant on Heard Island today, with Scott's (1988) vegetation categories of patchy cushion carpet and dense cushion carpet dominated by *A. selago* being most common. Secondly, *A. selago* exhibits wide ecological amplitude.

There are a number of salient features to table 3. The ubiquitous nature of *A. selago* is highlighted, occurring in all 15 ecological groups. *Azorella selago* was recorded from 80% (379/475) of all quadrats in this study. Six other species/species complexes can be classified as having wide ecological amplitude: the bryophytes *Dicranoweisia* spp., *Polytrichastrum alpinum, Fossombronia australis, Bartramia patens* and *Ceratodon purpureus* and the vascular species *Poa kerguelensis* and *Colobanthus kerguelensis*. Interestingly *Dicranoweisia* ssp. and *Ceratodon purpureus* were also recorded as having wide distributions on the island (table 3).

TABLE 3
Frequency of occurrence of taxa in each of the 15 TWINSPAN groups*

Cluster		Twinspan Groups														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
a	*Dicranella* sp.	12	22	28	10		3			9		22				
a	*Sainionia uncinata*	56	31	68	50	7				18	18	61	54			
a	*Cryptochila grandiflora*		2	5									8			
b	*Schistidium falcatum*		4	5	2				3					3		
b	*Cephaloziella varians*		17	40	44	7								7		
b	*Lophocoleoideae* sp.			7	8	60								7		
b	*Muelleriella crassifolia*		2	3	2	7								22		
b	*Pedinophyllopsis abdita*	6	83	60	73	80							8			
b	*Herzogobryum vermiculare*	6	9	5	6											
b	*Andreaea acuminata*		26	3	4		2		3	2						
b	*Psilopilum australe*		22	22	6											
b	*Schistidium* sp.		4													
b	*Verrucidens* spp.	18	54	5	2		3									
b	*Dicranoloma billardierii*	12	17	5	2											
b	*Pachyglossa fissa*	6	66	12	21											
b	*Blepharidophyllum densifolium*	6	84	12	6	14										
c	*Racomitrium crispulum*	62	46	33	85	87	5	22			6					
c	*Racomitrium lanuginosum*		4		6	7										
c	*Ditrichum immersum*	31	61	43	96	93	3	11								
c	*Herzogobryum atrocapillum*	18	26	5	19	73										
d	*Andreaea mutabilis*	100	20	35		7				7						
d	*Grimmia* sp.	25		3												
d	*Schistidium apocarpum*	75	9	8	4		3									
d	*Blindia robusta*	62	61	12			3				6					
d	*Ditrichum subaustrale*		6	12	8	7	3			2						
d	*Hennediella heimii*	12		3		7			3							
d	*Tortula geheebiaeopsis*		2	3					3							
d	*Cephaloziella exiliflora*	6	24	10	15		3		12	14		4				
e	*Poa kerguelensis*	1	19	5	54	73	94	89	90	5				7		
e	*Polytrichum piliferum*		4				6	50	16	18						
e	*Grimmia immerso-leucophaea*	56	20	3	10		43	72	10	5						
e	*Dicranoweisia* spp.	31	85	70	94	13	87	83	83	63	31	9		7		
f	*Colobanthus kerguelensis*		28	3	52	47	81	78	83	5	56	35	8	64		
f	*Polytrichastrum alpinum*	18	39	45	50	20	76	55	50	81	12	65	8			
f	*Ditrichum conicum*		54	30	8		30	28	43	47		30				
g	*Fossombronia australis*	6	54	50	38		37		33	54	62	70	85	17		
g	*Jungermannia coniflora*		4	12			2			2		26	8			
g	*Trichostomum* sp.		2	3	2		2				6					
h	*Pohlia wahlenbergii*	69	15	38	4		7		40	7		26	15			
h	*Bartramia patens*	56	56	70	65		21	5	70	49	50	70	15	3		
i	*Azorella selago*	6	93	85	98	86	100	77	67	88	94	100	23	75	69	100
j	*Ceratodon purpureus*		7	28		13	2	61	72	67	56	48	8	34		
j	*Bryum dichotomum*			3			2	17	6	5	19		69			
j	*Bryum pseudotriquetrum*		17	40	10		16		63	56	56	74				
k	*Pringlea antiscorbutica*		16	15	12	27	7		20	2	6	26		46		9
l	*Bryum* sp. 1			5					3	2		4		3		
l	*Bryum* sp. 2			18					3			4		11		
l	*Pohlia* sp.	12	36	3	6		2	5	33	46	56	48	61	7		
l	*Marchantia berteroana*	31							13	16		65		7		
m	*Acaena magellanica*									30	31	74	54		4	27
m	*Deschampsia antarctica*									2	6	48	69			
n	*Philonotis angustifolia*									2	6	17	38			
n	*Brachythecium* spp.	6	4	8					3	2	12	17	54	3		
o	*Poa cookii*		13	25	4		3	5	10	7	93	78	64	78	96	9
o	*Montia fontana*		2								50	9		28	13	
o	*Callitriche antarctica*			3							69	56	23	34	35	
	Number of quadrats/groups	17	54	40	51	15	67	18	30	42	16	23	13	31	22	22

* Expressed as a percentage of the total number of quadrats/groups. TWINSPAN Taxon Clusters (fig. 1) indicated by letters a–o.



Taxa in Cluster a generally occur between Groups 1–4 and 9–12. Clusters **b**, **c** and **d** have particularly strong frequencies of occurrence in Groups 1–5 (table 3). Clusters **e**–**l** are generally widespread across the groups with a number of common taxa (taxa with high frequencies of occurrence). Clusters **m**, **n** and **o**, with the exception of *P. cookii,* are generally confined to Groups 10–15.

Bryophyte species richness is particularly high in Groups 1–4 and relatively low in Groups 7, 12 and 13. Bryophyte taxa are absent from Groups 14 and 15. Vascular species richness is less varied, highlighting Scott's (1990) observation that one of the features of the vegetation of Heard Island vegetation is the small number of vascular species occupying a large range of habitats. However, Group 1 contains only two vascular species, *P. kerguelensis* and *A. selago.*

Details of each of the 15 TWINSPAN Groups are included in the appendix.

ECOLOGICAL NOTES ON IMPORTANT TAXA

Following are descriptions of life form (Gimingham & Birse 1957), ecological amplitude and ecological strategies of abundant or significant terrestrial plant taxa on Heard Island.

Bryophytes

Bartramia patens

Life form: Single moss stems to loose moss carpets.

Ecological amplitude: Although not extensive in cover, *Bartramia patens* is a widespread species on Heard Island. It is particularly prevalent in micro-habitats that are moist and have low light levels, such as between rocks.

Notes: As on Heard Island, *B. patens* is usually found in sheltered or shaded habitats on Macquarie Island. Hebrard (1970) reported *Bartramia* as occurring preferentially on acidic environments on Îles Kerguelen and Îles Crozet.

Dicranoweisia species complex

Life form: Moss cushion and turf including aquatic, black, loose turf in creeks.

Ecological amplitude: Dicranoweisia species complex is the most abundant bryophyte taxon on Heard Island. It exhibits wide ecological amplitude being recorded from most vegetated areas. The taxon appears to be a successful stress tolerator. Exceptions include areas of very high animal disturbance and lush vegetated areas inundated with surface water flow. Extensive turfs of *Dicranoweisia* spp. can be found, similar to those of *Ditrichum immersum.* In bryophyte-dominated areas, cover dominance or co-dominance of this taxon suggests that *Dicranoweisia* spp. are competitively successful. However, the relative cover of the taxon is reduced in areas of extensive stands of *Azorella selago.*

Notes: Dicranoweisia spp. occur on Marion and Prince Edward Islands in environments similar to those on Heard Island, but they do not appear to play such a dominant role.

FIG. 1 (left) — Dendrogram showing TWINSPAN taxon classification of bryophytes and vascular plants, based on presence/absence data.

Ditrichum immersum

Life form: Moss cushion and turf

Ecological amplitude: The species occurs as cushions and turfs in mesic and exposed sites where wind driven mist is the predominant moisture source. The species is generally in areas with stable substrates distant from the coast. At some sites, *D. immersum* cushions and turfs coalesce to form extensive bryophyte stands (pl. 1B) with other taxa such as *Dicranoweisia* spp.

Notes: Ditrichum immersum is particularly abundant in the northern and southern ice-free areas on Heard Island. Hebrard (1970) reported the genus *Ditrichum* as occurring preferentially on acidic environments on Îles Crozet and Îles Kerguelen. However, on Heard Island, *D. immersum* was found growing on limestone-derived moraine on the southern side of the Laurens Peninsula, as well as at other sites. Moist, limestone-derived moraines are likely to be alkaline.

Polytrichastrum alpinum

Life form: Open carpet moss.

Ecological amplitude: Polytrichastrum alpinum exhibits wide ecological amplitude on Heard Island. The species usually grows as small, loose, open carpets in gravel or ash/sand or single stems growing between branches of *Azorella selago.*

Notes: This species exhibits similar ecological amplitude on Marion and Prince Edward Islands, Macquarie Island and in alpine N.S.W. The extensive rhizoidal matting of this species, along with the root systems of *Colobanthus kerguelensis* and *Poa kerguelensis,* may contribute significantly to the stabilisation of bare ground on Heard Island.

Racomitrium crispulum

Life form: Moss turf.

Ecological amplitude: Racomitrium crispulum is a wide-ranging species on Heard Island, recorded from dry to mesic sites and from coastal to 250 m a.s.l. Single species turfs were usually found growing in gravel/ash/sand substrates. Often the species was a component of mixed turfs, on a variety of substrates such as thin peaty layers over lava. Although the species is widespread, total cover in any one area was not high.

Notes: On Macquarie Island, *R. crispulum* is a major component of vegetation in feldmark terraces, where extensive turfs of the species occur on terrace risers (Bergstrom & Selkirk 1999). Comparable turfs were not found on Heard Island: the niche occupied by *R. crispulum* on Macquarie Island appears to be filled by *Dicranoweisia* spp. on Heard Island.

Sainionia uncinata

Life form: Range from moss carpets to mats.

Ecological amplitude: Sainionia uncinata was recorded generally in mesic to hydric sites, on both lava and moraine. Lush carpets were recorded in areas of lateral surface drainage. In drier sites the species grows in a tighter mat form.

Vascular plants

Azorella selago

Life form: Cushion, with extensive tap root system and contractile roots (Ashton & Gill 1965).

Ecological amplitude: Azorella selago is by far the most widespread, abundant and dominant plant species on Heard Island. It was recorded in 80% of all quadrats surveyed in this study and occurred in all of the 15 TWINSPAN Groups. It occurs throughout the range of environments in which terrestrial plants grow on Heard Island: from coastal beaches up to 400 m a.s.l., from protected to exposed sites pl. 1C, D). In some areas it can even be found growing in a semi-aquatic environment, such as on the edge of Spit Bay Hut Creek. It is a successful coloniser of moraine slopes and other unstable ground. Shallow substrates appear to restrict the growth of *A. selago* cushions. Other limiting factors appear to be the very steep slopes and extreme environments, which occur with increasing altitude and limit all other plant growth on the island. *Azorella selago* can clearly be described as a "tolerator" and, considering its dominance of vegetated areas on Heard Island at present, a relatively successful competitor in most areas.

Notes: Vegetation dominated by *Azorella* sp. can be found on all Subantarctic island groups other than South Georgia (Greene & Walton 1975).

Colobanthus kerguelensis

Life form: Very small, low-growing, flowering cushion plant.

Ecological amplitude: Colobanthus kerguelensis is another species with very wide ecological amplitude. The species generally grows in gravel or ash/sand. It was recorded from most vegetated areas, exceptions being high-altitude, rocky habitats and areas of extensive animal disturbance.

Notes: Scott (1990) reported *C. kerguelensis* growing in crevices between rocks and in the lee of boulders on well-drained moraines on Heard Island. These micro-habitats are likely to be areas of greater moisture availability or protection from wind exposure.

Poa cookii

Life form: small tussock grass.

Ecological amplitude: Poa cookii is widespread on Heard Island, occurring from coastal to high altitudes. The species is an effective indicator of nutrient-enriched soil conditions. Extensive stands occur near seal and seabird areas.

Notes: Similar patterns of distribution of this species have been reported on Marion and Prince Edward Islands (Gremmen 1982) and can also be found on Macquarie Island but to a lesser extent, affected by competition from more aggressive tussock grasses.

Poa kerguelensis

Life form: Small tufted grass, generally less than 20 cm high.

Ecological amplitude: This species is considerably widespread but very rarely forms extensive stands (some swards were recorded at the base of Macey Cone, Laurens Peninsula, with a cover of greater than 50%). Generally the species occurs as sporadic tufts. Of the 163 records of *P. kerguelensis* from quadrats in the vegetation survey, 154 of these had cover values of 5% or less. The species is prevalent in gravels and sands. It is common in xeric, exposed conditions, although it also grows on stream banks. The species can be found in relatively unstable substrates, such as in areas of frost-heaving, ice-cored moraines and stream banks, and appears to possess characteristics of a ruderal species. It was not recorded in environments with enriched nutrient status or animal disturbance.

Notes: Hughes' (1987) report of *P. kerguelensis* only from feldmark categories is an under-representation of distribution of the species. It is widely distributed in Hughes' cushion carpet category. Scott (1990) recorded *P. kerguelensis* in areas similar to those described here, as well as sites recently exposed by glacial recession, post-1947.

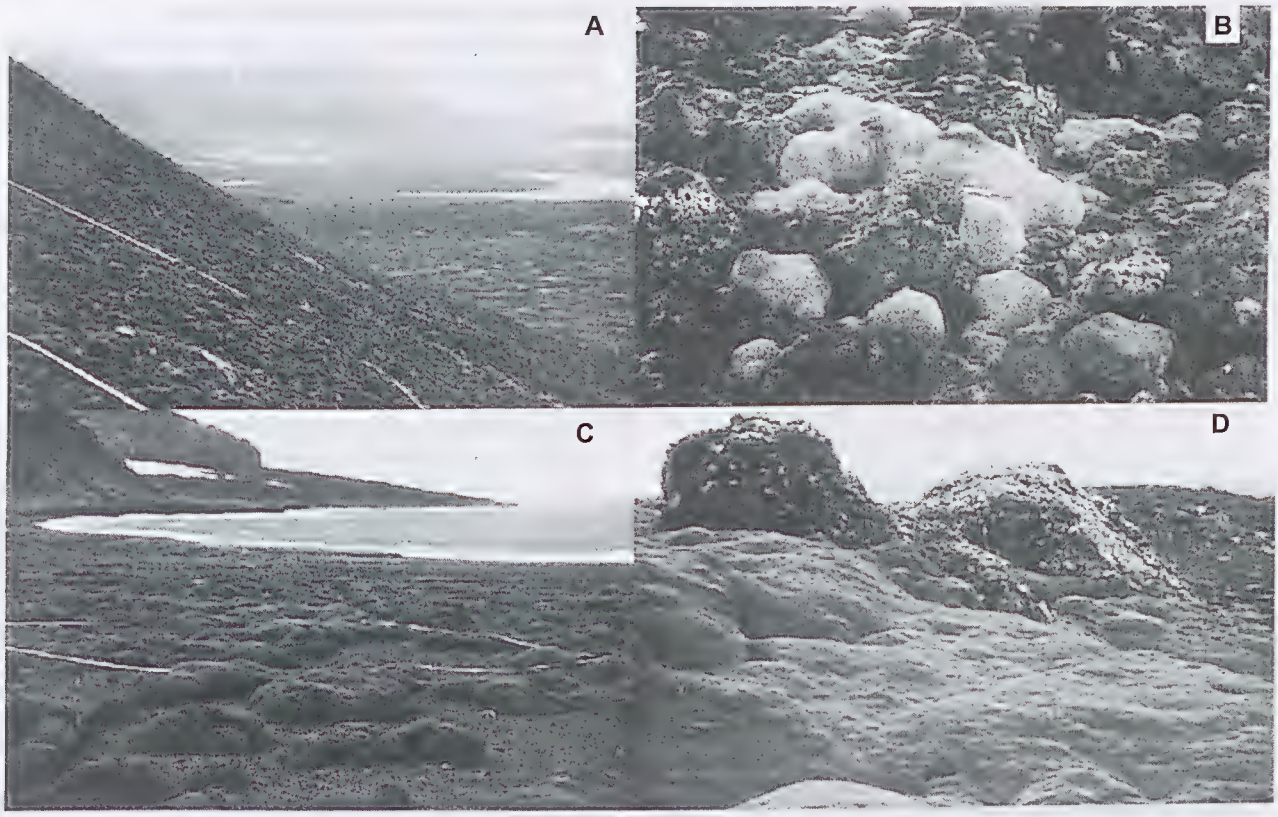


PLATE 1
(A) TWINSPAN Group 4. Slope of Corinth Head (scoria cone), Azorella Peninsula. A mix of bryophyte and Azorella selago *vegetation cover. (B) TWINSPAN Group 2. Lush cover of mosses* Blindia robusta *and* Ditrichum immersum, *Deacock Moraine, Long Beach. (C) TWINSPAN Group 6.* Azorella selago *cushions with occasional moss polsters of* Dicranoweisia *spp. (D) TWINSPAN Group 15. Dense* A. selago *cushion carpet.*

Pringlea antiscorbutica
Life form: Perennial suffrutescent herb, up to 60 cm tall.
Ecological amplitude. Pringlea antiscorbutica is widespread on Heard Island, occurring from coastal environments to the extreme limits of plant growth at higher altitudes. Hughes (1987) reported *P. antiscorbutica* at low frequencies in all her vascular plant community categories. She described the species as an "opportunistic species which colonises newly disturbed areas such as landslides and recently deposited moraines". Scott (1988) reported the species growing along edges of gravelly streams, lakes, old river terraces and on scree slopes, and also luxuriant growth of *P. antiscorbutica* adjacent to penguin colonies and monospecific stands on sheltered moraine slopes. *Pringlea antiscorbutica* can be considered to be an effective ruderal species, occurring preferentially on gravel or ash/sand substrates particularly in morainic debris. Many of the moraine sites are ice-cored and/or unstable.
Notes: Young & Schofield (1973) suggested that on Îles Kerguelen "*Pringlea* is tolerant of low temperatures and high winds, but requires a continuous supply of moisture and good drainage". This description is consistent with the distribution of the species on Heard Island. Young & Schofield also reported (1973) from microfossil studies that *Pringlea* was present on Îles Kerguelen during the last glacial maximum and suggested that the species is a remnant of a Tertiary Kerguelen flora. As a result of recent studies on Îles Kerguelen, *P. antiscorbutica* is described as occurring from sea-level to 1000 m altitude in conditions of salinity, high wind exposure, permanent cold temperatures and frequent freeze–thaw cycles, and as having the widest ecological amplitude of the flowering plants in the region (Hennion 1992, Hennion & Bouchereau 1998).

NOTES ON OTHER TAXA

The following species, although not as significant and widespread as those listed above, are characteristic components of some vegetation on Heard Island.

Liverworts

Blepharidophyllum densifolium
Generally recorded from stable mesic rocky feldmark sites often with *Pedinophyllopsis abdita.*

Fossombronia australis
Very widespread on Heard Island but was never recorded as abundant at any particular site. It was generally seen growing in gravel at the edge of *Azorella selago* cushions or growing between branches of *A. selago* with rhizoids anchored in a mixture of humic material such as abscised leaves and accumulated wind blown sediment.

Herzogobryum atrocapillum
A very tiny, threadlike liverwort. It was recorded mainly from mesic scoria and stable rocky moraines with high bryophyte cover. Single stems were commonly found interwoven with other bryophytes.

Pedinophyllopsis abdita
A common liverwort in the northern and southern regions of Heard Island. It was recorded from a range of coastal to high altitude mesic environments, but generally not in sites with significant nutrient enrichment. It grows as a mat or as single stems entangled with other plants.

Mosses

Andreaea mutabilis and *Schistidium apocarpum*
Rock-colonising bryophytes that were commonly growing in stable areas on large scoria boulders or rocks in moraine. Many records of these species were at high altitude sites such as on Deacock Moraine, Long Beach region.

Blindia robusta
Occurs in extensive lush stands on moraine, cliffs and lava on the eastern and southern sides of Heard Island (pl. 1B).

Brachythecium species
Generally confined to areas of lateral water flow, such as on slopes below springs or in areas of meltwater drainage from ice-cored moraines. Scott (1990) reported *Brachythecium* spp. growing on wet cliff ledges below waterfalls.

Bryum pseudotriquetrum
Another widespread but not abundant bryophyte on Heard Island. It was often recorded as single stems amongst *Azorella selago* cushions, but could also be found in hydric zones such as at the edge of glacial lakes and streams in meltwater areas in generally unvegetated ice-cored moraines. Scott (1988) reported *B. pseudotriquetrum* with *Pohlia wahlenbergii* colonising areas exposed to spray from waterfalls.

Ceratodon purpureus
Like *Fossombronia australis,* widespread on Heard Island but never recorded as very plentiful. It was most commonly found growing in gravel and spanned a large range of environments from xeric exposed moraines to flush zones.

Polytrichum piliferum
Recorded on Heard Island only from moraines. It generally grows in gravel or fines and appears to tolerate xeric conditions and unstable substrates, anchoring to the substrate with rhizoidal mats.

Vascular Plants

Acaena magellanica
Recorded from the southeastern ice-free areas on Heard Island, between Fifty-one Glacier and Fairchild Beach (Scott 1988). This species most often grows on moist slopes, generally in association with other species such as *Azorella selago* and *Poa cookii.* Scott (1988) also reported it growing with *Pringlea antiscorbutica.*

Callitriche antarctica and *Montia fontana*
Restricted to nutrient enriched, moist environments such as the edges of seal wallows (Hughes 1987, Whinam 1989, Scott 1989). *Montia* appears to have a restricted distribution on the island (Scott 1988).

Deschampsia antarctica
Has been noted in the eastern areas on Heard Island growing in drainage lines and springs (Hughes 1987, Scott 1988).

CONCLUSION

Heard Island has an extremely varied range of terrestrial environments in which distinct suites of species occur. This study has begun to describe the ecological amplitude of these species. There are two striking features of terrestrial plant ecology on Heard Island. The first is the dominance of bryophytes in terms of species richness; the second is the dominance of *Azorella selago* in terms of abundance and distribution.

Though *Azorella* occurs on most of the other Subantarctic islands, its distribution on these islands is restricted, generally to higher altitudes or exposed situations. Bergstrom *et al.* (1997) reviewed data on *Azorella* spp. in the Subantarctic. Generally *Azorella* (both *A. selago* and *A. macquariensis*) exhibit slow growth rates, slow floral development and limited successful sexual reproduction; they are outcompeted by more aggressive and/or taller plant species. With the cooler temperatures and limited vascular flora of Heard Island, *A. selago* is not subjected to significant competition from other vascular species.

There is, however, a very high chance that this situation will change with time. Climatic amelioration in association with glacial retreat will create opportunities for new species to colonise, become established and ultimately interact with the species already established on the island.

There has been minimal human impact on the terrestrial ecosystem of Heard Island. Chown *et al.* (1998), predictably found a relationship between species introduced by humans and the number of human occupants and/or visitors to Subantarctic islands. Bergstrom & Chown (1999) concluded that functional groups previously not found on Subantarctic islands have a substantial likelihood of becoming invasive and that warmer conditions will increase the ease with which this can happen. Given the low species diversity on Heard Island, the spectrum of potential invasive plants is very large.

This study provides a baseline from which to recognise and document change in the terrestrial ecosystems of the island. The combination of climate change and increased ecotourism interest, makes ecological change on Heard Island inevitable.

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APPENDIX
TWINSPAN group details

TWINSPAN Group 1, n = 17 quadrats
Mean altitude: high >200 m a.s.l.
Moisture: mesic
Wind exposure: medium
Mean substrate depth: 5 cm
Mean rock cover: 37%
Mean bare ground cover: 10%
Mean total bryophyte cover: 47%
Mean Azorella selago *cover:* 1%
Geomorphology: exclusively moraine, "boulder scree"
TWINSPAN indicator species: Andreaea mutabilis & *Schistidium apocarpum*
Community categories: overwhelming feldmark
Notes: Group 1 consists of quadrats from one local area, Deacock Moraine, Long Beach. The group is characterised by a predominance of bryophytes, both in species richness (26 taxa) and cover. In some quadrats, bryophyte cover exceeded 80%. The ground was stable, rocky moraine with minimal skeletal soil development. This is highlighted by the two indicator species, the mosses *Andreaea mutabilis* and *Schistidium apocarpum* being rock colonisers. Lichens, including *Usnea* sp. were also abundant on exposed rock. Areas with a developed peaty layer (2–5 cm) had developed lush turves and carpets dominated by either/and *Dicranoweisia* spp., *Blindia robusta* and *Sainionia uncinata*. Only two vascular species, *Poa kerguelensis* and *Azorella selago* were recorded, both with sparse cover.

TWINSPAN Group 2, n = 54
Mean altitude: medium, 50 m a.s.l.
Moisture: mesic
Wind exposure: medium
Mean substrate depth: 15 cm
Mean rock cover: 11%
Mean bare ground cover: 18%
Mean total bryophyte cover: 35%
Mean Azorella selago *cover:* 16%
Geomorphology: lava and stable moraines
TWINSPAN indicator species: Blepharidophyllum densifolium and *Verrucidens* spp.
Community categories: predominantly feldmark
Notes: Group 2 consists of quadrats in which bryophytes are overwhelmingly the dominant component, both in terms of cover and diversity (40 taxa in total). Thirty-three quadrats had lush bryophyte carpets, exceeding 50%. Stability of habitat appeared to be an important factor and shallow substrate depth reduced competition from *Azorella selago*. Major bryophyte species included *Blindia robusta, Ditrichum immersum, Dicranoweisia* spp. and *Bartramia patens* as well as the indicator taxa. This group included sites in the Mt Drygalski area, Long Beach (pl. 1B) and lavas on the Laurens Peninsula, as well as sites on limestone at the southern base of Anzac Peak.

TWINSPAN Group 3, n = 40 quadrats
Mean altitude: medium, 50 m a.s.l.
Moisture: mesic
Wind exposure: medium
Mean substrate depth: 18 cm
Mean rock cover: 13%
Mean bare ground cover: 20%
Mean total bryophyte cover: 27%
Mean Azorella selago *cover:* 23%
Geomorphology: varied, lava – scoria and flows, moraines and sand
TWINSPAN indicator species: Sainiona uncinata
Community categories: dense cushion carpet, patchy cushion carpet and feldmark.
Notes: As with Group 2, bryophyte diversity is very high (total 42 taxa), with the main distinguishing feature between this group and Group 2 being prominence of *Azorella selago*. Carpets of *Sainionia uncinata* were also recorded. The presence of this species is a good indication of mesic conditions. *Dicranoweisia* spp. and *Ditrichum immersum* were also abundant bryophyte taxa, with *Blindia robusta* less conspicuous. Ten quadrats in Group 3 had *Poa cookii* present, perhaps reflecting slightly higher nutrient status. Sites were recorded from stable lava or moraine, or sand such as on streams banks. Group 3 included sites from all major vegetated regions as well as Capes Pillar, Arkona and Gazert.

TWINSPAN Group 4, n = 51 quadrats
Mean altitude: high, 90 m a.s.l.
Moisture: mesic
Wind exposure: medium to exposed
Mean substrate depth: 11 cm
Mean rock cover: 15%
Mean bare ground cover: 22%
Mean total bryophyte cover: 33%
Mean Azorella selago *cover:* 11%
Geomorphology: predominantly lava scoria and flows
TWINSPAN indicator species: Dicranoweisia spp. and *Bartramia patens*
Community categories: patchy cushion carpet and feldmark
Notes: Group 4 contains quadrats similar in species composition to Groups 2 and 3. Bryophyte species richness is fairly high (total 34 taxa). However, sites are mainly on lava and are more exposed and drier than those in the previous two groups. *Azorella selago* cover is low. Sites include areas at the base of Macey Cone and on the slopes of Corinth Head (pl. 1A). Lava ridges southwest of Cape Cartwright and the higher vegetated slopes of Deacock Moraine.

TWINSPAN Group 5, n = 15 quadrats
Mean altitude: high 90 m a.s.l.
Moisture: predominantly xeric
Wind exposure: exposed
Mean substrate depth: 10 cm
Mean rock cover: 25%
Mean bare ground cover: 23%
Mean total bryophyte cover: 45%
Mean Azorella selago *cover:* 5%
Geomorphology: predominantly scoria
TWINSPAN indicator species: Herzogobryum atrocapillum and *Lophocolea* sp. 1.
Community categories: feldmark
Notes: Group 5, with very exposed scoria slopes, represents the extreme end of a continuum from Groups 2–4. Although very exposed the sites were mesic from deposition of wind-driven moisture. Bryophyte species richness was low, although total bryophyte cover was high, suggesting reduced habitat

variety. *Azorella selago* cover was low, again reflecting shallow substrate depth. Most sites were on high slopes of Macey Cone.

TWINSPAN Group 6, n = 67
Mean altitude: medium 40 m a.s.l.
Moisture: predominantly xeric
Wind exposure: exposed
Mean substrate depth: 18 cm
Mean rock cover: 18%
Mean bare ground cover: 39%
Mean total bryophyte cover: 11%
Mean Azorella selago *cover:* 20%
Geomorphology: exclusively moraine
TWINSPAN indicator species: Fossombronia australis
Community categories: generally patchy cushion carpet
Notes: Most sites in Group 6 were from the Dovers Moraine area, Spit Bay and Long Beach area (pl. 1C). The sites were generally characterised by small *Azorella selago* cushions with occasional clusters of small moss polsters, surrounded by windswept gravel. In some sites there was evidence of frost raking and nubbin formation running parallel with the prevailing wind direction. The indicator species, *Fossombronia australis,* most often was found having colonised the edges of or spaces between branches of *A. selago* cushions. *Azorella selago, Poa kerguelensis, Colobanthus kerguelensis, Dicranoweisia* spp. and *Polytrichastrum alpinum* were recorded from most of the 67 quadrats in this group.

TWINSPAN Group 7, n = 18
Mean altitude: medium, 60 m a.s.l.
Moisture: predominantly xeric
Wind exposure: exposed
Mean substrate depth: 10 cm
Mean rock cover: 38%
Mean bare ground cover: 37%
Mean total bryophyte cover: 7%
Mean Azorella selago *cover:* 8%
Geomorphology: exclusively moraine
TWINSPAN indicator species: Ceratodon purpureus and *Polytrichum piliferum*
Community categories: feldmark
Notes: This group represents an extension from Group 6, with most sites on Dovers Moraine. Most sites were extremely exposed and xeric. Many sites had evidence of periglacial activity such as nubbin, frost-raking and sorted pavement. There was little vegetation, either bryophytes or vascular plants. Species diversity was low. The indicator species, *Ceratodon purpureus* and *Polytrichum piliferum,* were often found growing in gravel and fines and appeared to tolerate surface movement.

TWINSPAN Group 8, n = 30
Mean altitude: medium, 50 m a.s.l.
Moisture: xeric to medium
Wind exposure: exposed to protected
Mean substrate depth: 18 cm
Mean rock cover: 40%
Mean bare ground cover: 11%
Mean total bryophyte cover: 15%
Mean Azorella selago *cover:* 14%
Geomorphology: exclusively moraine
TWINSPAN indicator species: Poa kerguelensis and *Colobanthus kerguelensis*
Community categories: patchy cushion carpet
Notes: Group 8 is another variation on Group 6, occurring in drainage lines and beside streams. The sites were wetter than those of the previous groups, and this is reflected in a high number of Bryaceae taxa occuring in some quadrats (see table 2). The sites were exclusively in the Dovers Moraine area, Spit Bay.

TWINSPAN Group 9, n = 30 quadrats
Mean altitude: medium low, 35 m a.s.l.
Moisture: xeric to hydric
Wind exposure: exposed to medium
Mean substrate depth: 47 cm
Mean rock cover: 5%
Mean bare ground cover: 14%
Mean total bryophyte cover: 19%
Mean Azorella selago *cover:* 43%
Geomorphology: predominantly moraine
TWINSPAN indicator species: Polytrichastrum alpinum
Community categories: mixed
Notes: Group 9 consists of quadrats which would span all of Hughes' (1987) community categories except maritime grassland. The common feature of the sites was that they were generally on moraine, and common taxa included *Azorella selago* (with high cover values) and the indicator species, *Polytrichastrum alpinum.* Unconsolidated substrate depth was high with a mean of 47 cm, this being an underestimate as many sites had depth greater than the limit of measurement (100 cm). Most sites were in the Dovers Moraine area.

TWINSPAN Group 10, n = 16 quadrats
Mean altitude: low, 30 m a.s.l.
Moisture: hydric
Wind exposure: medium to protected
Mean substrate depth: 56 cm
Mean rock cover: 0%
Mean bare ground cover: 12%
Mean total bryophyte cover: 11%
Mean Azorella selago *cover:* 32%
Geomorphology: predominantly moraine
TWINSPAN indicator species: Montia fontana
Community categories: Predominantly pool complex and patchy cushion carpet
Notes: This group contains quadrats on or near impeded drainage areas on moraine substrates close to the coast. This is reflected by the indicator species being *Montia fontana.* The sites generally have large coalescing cushions of *Azorella selago* with deep, unconsolidated substrates or peat depths exceeding 100 cm at many sites. Many cushions flank pools. Nutrient status of the sites was high, with the nitrophiles *Poa cookii* and *Callitriche antarctica* in the majority of the quadrats. The source of nutrient enrichment was the wallows of elephant seals. Bryophytes consisted mainly of small cushions of *Dicranoweisia* spp. at the edge of *A. selago* cushions, *Polytrichastrum alpinum* growing in gravel, *Fossombronia australis* growing beside or in *A. selago* cushions and *Brachythecium* spp. growing in moist or wet areas at the edge of pools. The sites had wide distribution including areas in Dovers Moraine, Long Beach and Atlas Cove.

TWINSPAN Group 11, n = 23 quadrats
Mean altitude: medium to low, 20 m a.s.l.
Moisture: hydric
Wind exposure: medium to protected
Mean substrate depth: 50 cm
Mean rock cover: 0%
Mean bare ground cover: 3%
Mean total bryophyte cover: 56%
Mean Azorella selago *cover:* 16%
Geomorphology: exclusively moraine
TWINSPAN indicator species: Marchantia berteroana
Community categories: mixed; however, meadow and herbfield more common
Notes: Group 11 consisted mainly of wet sites which could be classified as meadow and herbfield. Vegetation cover was high and total bryophyte cover was very extensive. Major vascular species included mats of *Acaena magellanica* and tufts of *Deschampsia antarctica* and *Poa cookii*. *Azorella selago* occurred in all quadrats of this group, although it was not a dominant species in terms of cover. Major bryophyte species included mats of *Marchantia berteroana,* lush carpets of *Sainionia uncinatus* and turves of *Bryum pseudotriquetrum.* Many sites had peat depths exceeding 100 cm. Sites were recorded from Sydney Cove, Long Beach and Dovers Moraine.

TWINSPAN Group 12, n = 13 quadrats
Mean altitude: low, 15 m a.s.l.
Moisture: mesic
Wind exposure: medium
Mean substrate depth: 30 cm
Mean rock cover: 7%
Mean bare ground cover: 1%
Mean total bryophyte cover: 50%
Mean Azorella selago *cover:* 7%
Geomorphology: exclusively moraine
TWINSPAN indicator species: Brachythecium spp.
Community categories: Predominantly meadow
Notes: Group 12 consisted mainly of quadrats containing *Deschampsia antarctica*. *Azorella selago* abundance was very low and in comparison with Group 11, sites were drier and mean substrate depth considerably shallower. The indicator taxa, *Brachythecium* spp., often occurred as thick carpets.

TWINSPAN Group 13, n = 31 quadrats
Mean altitude: low, 15 m a.s.l.
Moisture: xeric to mesic
Wind exposure: medium
Mean substrate depth: 28 cm
Mean rock cover: 12%
Mean bare ground cover: 23%
Mean total bryophyte cover: 7%
Mean Azorella selago *cover:* 20%
Geomorphology: predominantly moraine
TWINSPAN indicator species: Colobanthus kerguelensis
Community categories: mixed but predominantly coastal
Notes: Quadrats in Group 13 were generally from salt-affected coastal sites, including areas that could be classified as maritime grassland, pool complex and low-lying, patchy cushion carpet. Sites were at Sydney Cove, Spit Bay and Atlas Cove, including the supralittoral zone at Atlas Cove. *Colobanthus kerguelensis* as an indicator species most likely reflects small-scale xeric conditions. Bryophyte richness was low; however, one notable feature was the presence of *Muelleriella crassifolia* ssp. *acuta* in all the supralittoral quadrats. A high occurrence of *Poa cookii* throughout reflected a high nutrient status, perhaps blown in from nearby animal disturbed sites.

TWINSPAN Group 14, n = 21 quadrats
Mean altitude: low, 13 m a.s.l.
Moisture: mesic
Wind exposure: exposed
Mean substrate depth: 41 cm
Mean rock cover: 1%
Mean bare ground cover: 27%
Mean total bryophyte cover: 0%
Mean Azorella selago *cover:* 21%
Geomorphology: predominantly moraine
TWINSPAN indicator species: Poa cookii
Community categories: predominantly maritime grassland
Notes: Group 14 consists of coastal sites near penguin colonies and seal-wallowing areas at Spit Bay and seal-wallowing areas at Atlas Cove, and an area approximately 500 m inland from Long Beach. *Poa cookii* was the dominant species. No bryophyte taxa were recorded in these quadrats, most likely reflecting animal disturbance and toxic nutrient levels.

TWINSPAN Group 15, n = 22 quadrats
Mean altitude: medium, 33 m a.s.l.
Moisture: mesic
Wind exposure: exposed
Mean substrate depth: 65 cm
Mean rock cover: 0%
Mean bare ground cover: 6%
Mean total bryophyte cover: 0%
Mean Azorella selago *cover:* 68%
Geomorphology: moraine or sand
TWINSPAN indicator species: Pringlea antiscorbutica
Community categories: predominantly cushion carpet
Notes: Group 15 sites had a very high *Azorella selago* cover and the occasional occurrence of *Pringlea antiscorbutica*, *Poa cookii* and *Aceana magellanica* (pl. 1D). *Pringlea antiscorbutica* as an indicator species is not considered to be conclusive. As data was reduced to a presence/absence basis, the extensive cover of *Azorella selago* in quadrats in Group 15 was not highlighted in the TWINSPAN analysis, as *A. selago* occurred in 80% of all the quadrat survey in the study. Group 15 sites were recorded from areas of Dovers Moraine, Long Beach, Atlas Cove and the southern side of the Laurens Peninsula. Unconsolidated substrate depth in these areas often exceeded 100 cm.

CHANGES IN HEARD ISLAND GLACIERS, KING PENGUINS AND FUR SEALS SINCE 1947

by G. M. Budd

(with two tables, three text-figures and one plate)

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The purpose of this paper is to summarise and discuss the changes in glaciers, king penguins and fur seals reported by the nine wintering parties and 11 summer expeditions that have visited Heard Island since 1947, with emphasis upon those of the years between 1947 and 1971. These early years were notable for an initial period (1947–55) of minimal change, and a subsequent period (1963–71) of rapid change in which a complex pattern of asynchronous glacier retreat and readvance was observed and the main features of the island's recolonisation by king penguins and fur seals were established. Subsequent expeditions (1980–93) have reported continuing glacier recession, evidently in response to warmer air temperatures, and a continuing exponential increase in king penguins and fur seals. The glacier observations show that the Heard Island glaciers are sensitive indicators of climate change in the Southern Ocean, and of the interactions between climate and glacier topography. The island's recolonisation by king penguins and fur seals is attributed mainly to an improved food supply which may itself, like the glacier recession, be a response to changes in atmospheric and oceanic circulation. Glacier recession and its consequences are changing the island's coastline, and the expanding populations of king penguins and fur seals are damaging the vegetation. All these phenomena, occurring as they do in an island with a hitherto undamaged ecosystem and no introduced predators, clearly warrant continuing study.

Key Words: expedition history, glacier fluctuations, king penguins, fur seals, recolonisation, habitat preferences, climate change, atmospheric patterns, oceanic circulation patterns, Heard Island.

INTRODUCTION

Over the past 50 years Heard Island has experienced widespread glacier recession, together with rapid recolonisation by king penguins (*Aptenodytes patagonica*) and fur seals (*Arctocephalus gazella*). The most recent observations show that several glaciers now terminate at the head of broad lagoons, 1–2 km inland from their former coastal ice cliffs (Garvin *et al.* 1999), and that in 1992–93 there were approximately 11 000 breeding pairs of king penguins (Green *et al.* 1998), 350 fur seal pups (Shaughnessy *et al.* 1998) and 22 000 non-breeding fur seals (Green 1993b).

These changes are interesting in themselves, as large-scale and strangely concurrent natural phenomena; in their consequences, which include alterations in the island's coastline and vegetation; and in their potential causes, which include climate change, volcanic activity, and changes in terrestrial and marine ecosystems.

Although the changes in glaciers, king penguins and fur seals have been documented since their beginnings by members of the nine wintering parties and 11 summer expeditions that have visited the island since 1947 (table 1), the information is scattered among numerous papers and reviews that deal with each topic separately. There is no single publication that brings together the evidence on all three. The purpose of this paper, therefore, is to provide a convenient summary and discussion of the observations, with emphasis upon those of the years between 1947 and 1971. These early years were notable for an initial period (1947–55) of minimal change, and a subsequent period (1963–71) of rapid change in which a complex pattern of asynchronous glacier retreat and readvance was observed and the main features of the island's recolonisation by king penguins and fur seals were established. In what follows, the history of expeditions to the island is summarised; the observed changes in glaciers, king penguins and fur seals are described and discussed, together with some of their consequences; and finally their possible causes are considered.

EXPEDITION HISTORY

Early history (1855–1929)

Heard Island was continuously occupied by sealers for almost three decades after the first landing in 1855 (Downes 1996), and intermittently thereafter until the early 1930s (Roberts 1950, Law & Burstall 1953). Scientific observations were made — at the northwestern end of the island only — by the *Challenger* expedition in 1874 (Thomson & Murray 1885), by the *Gauss* expedition in 1902 (Drygalski 1908), and by Aubert de la Rue and the British, Australian and New Zealand Antarctic Research Expedition (BANZARE) in 1929 (Aubert de la Rue 1929, Price 1962).

Continuous ANARE occupation (1947–55)

From December 1947 until March 1955 Heard Island was continuously occupied by the Australian National Antarctic Research Expeditions (ANARE), which established a station at Atlas Cove (fig. 1) (Scholes 1949, Law & Burstall 1953, Law & Bechervaise 1957, Brown 1957, Veenstra & Manning 1982, Bowden 1997). Work away from the station area was done by unsupported field parties of two or three men travelling on foot, which repeatedly visited most parts of the coast and on two occasions made complete overland circuits. Thus, Spit Bay was visited in November 1948, 1949, 1950

TABLE 1
Scientific expeditions to Heard Island, 1947–93*

Year	Expedition	References
1947–55	Continuous occupation by ANARE wintering expeditions at Atlas Cove station	Law & Burstall 1953, Law & Bechervaise 1957, Bowden 1997
1963	ANARE expedition	Budd 1964a, b
1965	Private expedition (South Indian Ocean Expedition to Heard Island) in yacht *Patanela*	Anon 1965, Temple 1966, Tilman 1966
1969	ANARE expedition in USCGC *Southwind*	Budd 1970a
1969–70	US wintering expedition	Veenstra & Manning 1982
1971	ANARE party with French expedition in M.V. *Gallieni*	Gendrin 1971, Budd 1971, 1972a, Bowden 1997
1980	ANARE party with National Mapping expedition in M.V. *Cape Pillar*	Veenstra & Manning 1982
1983	Private expedition (Project Blizzard) in yacht *Anaconda II*	Vining 1983
1983	Private expedition (HIDXA) in whale chaser *Cheynes II*	Jenkins-Smith 1985, Smith 1986
1985	ANARE expedition	Burton & Williams 1986
1986–87	ANARE expedition	Ledingham 1987
1987–88	ANARE expedition	Kirkwood *et al.* 1989
1990	ANARE early winter expedition	Green 1990a
1992–93	ANARE wintering expedition	Green 1993a

* Expeditions were undertaken in summer, using ANARE ships, except where otherwise stated. ANARE = Australian National Antarctic Research Expeditions.

and 1951, as well as in July 1951 and December 1954; and Long Beach was visited during the circuit trips of 1951 and 1954.

The period 1947–55 yielded seven years of uninterrupted observations in meteorology and geophysics, and established the main features of the island's topography, geology, glaciology, and biology. It also yielded suggestive evidence of minor glacier recession, and hints of a slight increase in the numbers of non-breeding king penguins and fur seals that were visiting the island.

Subsequent expeditions (1963–93)

Except for the wintering parties of 1969 and 1992, all subsequent expeditions were undertaken in summer (table 1). The 1963 expedition obtained the first evidence of major glacier retreat and recolonisation by king penguins and fur seals, and the following expeditions recorded the progress of these phenomena. Heard Island is well suited for such studies. It is remote, uninhabited, and infrequently visited by humans; its ecosystem has not been damaged by past occupation; there are no introduced predators; and it

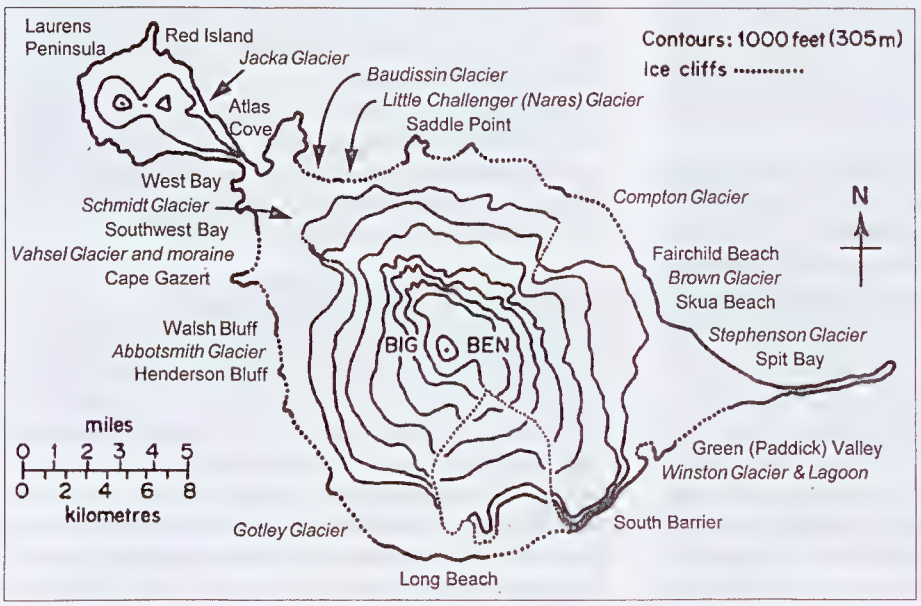

FIG. 1 — Heard Island (1948 map), showing places mentioned in the text.

presents sharp contrasts of terrain, glacier topography, and local climate.

Methods (1963–71)

The expeditions of 1963–71 benefited from consistency of field methods, in that the principal investigator took part in all four expeditions (as well as in the 1954–55 expedition and a brief visit in March 1960) and another observer took part in three of them. Glaciers were photographed from the same or similar viewpoints each year, and changes were assessed by reference to adjacent rock features. In these years the numbers of king penguins and fur seals at each locality were still small enough to permit accurate direct counts (confirmed by photography), without the problems, described elsewhere (Budd 1962), that large and dense concentrations of animals present. The techniques used for counting fur seals (Budd 1970c) yielded close agreement between observers and between repeat counts.

CHANGES IN GLACIERS, KING PENGUINS AND FUR SEALS

Glaciers

Overview (1874–1997)

The main features of the Heard Island glaciers have been described by Lambeth (1951) and by Allison & Keage (1986). Photographic and other records showed no apparent change between 1874 and 1929 but suggestive evidence of general minor recession by 1955, and by 1963 there was obvious major recession in most of the glaciers (Budd 1964a,b, Budd & Stephenson 1970). However, the next eight years brought a mixed pattern of asynchronous retreat and readvance (Budd 1973a), which is summarised in table 2. Subsequent observations (Allison & Keage 1986, Garvin *et al.* 1999) have shown continuing major recession. Details of the observations between 1963 and 1971 are given below.

TABLE 2
Glacier fluctuations at Heard Island from 1954 to 1971

Pattern/Glacier	Changes*			
	1963	1965	1969	1971
Continuous retreat				
Stephenson	R	R	R	R
Brown	R	R	R	R
Compton	R	†	R	R
Jacka	R	†	R	R
Schmidt	R	†	S	R
Readvance by 1965				
Winston – SW stream	R	A	†	A
Readvance by 1969				
Little Challenger (Nares)	R	†	A	S
Baudissin	R	†	A	S
Readvance by 1971				
Vahsel	R	†	R	A
Abbotsmith	†	†	†	R / A
Winston – NE sheet	R	S	†	A

* Changes shown are those detected since the previous year of observation, beginning with 1954. R, retreat; S, stationary; A, advance. Table modified from Budd (1973a).
† Not inspected. Abbotsmith glacier in 1971 was readvancing after having retreated 800 m since 1954.

1963

The greatest change was shown by the Winston Glacier, which had retreated approximately 1.5 km since 1947 and 0.8 km since 1954, and was now divided by a central rock promontory into (a) a southwest stream curving around South Barrier and (b) a northwest ice sheet descending from the eastern side of Big Ben and exposing high rocky bluffs above a beach on Winston Lagoon.

Striking retreat was also obvious elsewhere. On the northeast coast the terminal ice cliffs of the Stephenson and Brown Glaciers, which in 1954 were more than 15 m high and washed by the sea, had disappeared and the glaciers now terminated more than 100 m inland behind a beach and a lagoon. The tongue of the Compton Glacier, which in 1947 had extended out into the sea, had receded leaving a line of shoal water that suggested an early stage in the formation of a beach and lagoon.

In Corinthian Bay the Little Challenger Glacier (subsequently renamed the Nares), which in 1954 had terminated in 20 m sea cliffs, now had a sloping terminus behind a broad beach. The neighbouring Baudissin Glacier showed reduced thickness and lower sea cliffs, and its western tongue — the Schmidt Glacier — was reduced in width and thickness. In Southwest Bay the sea cliffs of the Vahsel Glacier were lower and round-edged, had retreated at their northern margin beside Erratic Point, and had developed extensive moraines at their southern margin near Cape Gazert. On the Laurens Peninsula the Jacka Glacier was greatly reduced in thickness, and its terminus had retreated from its 1954 position immediately behind the beach.

1965

Examination of the eastern half of the island showed further retreat of the Stephenson and Brown Glaciers. However, the Winston Glacier's southwestern stream had increased in thickness and readvanced more than 200 m, although its northwestern ice sheet was unchanged.

1969

Examination of all glaciers on the north and northeast coast showed that the Baudissin and Little Challenger had readvanced and now differed little from their 1954 appearance (Budd 1970a, 1973a, Budd & Stephenson 1970). The Baudissin had increased in thickness, and photographic comparisons with the known height of the adjacent Church Rock showed that the sea cliffs of its eastern part were now 30–40 m high instead of the 20–25 m observed in 1963. The Little Challenger had advanced and spread laterally, and had again developed sea cliffs 20 m high.

Further retreat was apparent in the Stephenson, Brown, Compton, Vahsel and Jacka Glaciers. The ice front of the Brown Glacier had retreated about 300 m in the six years since 1963. The shoal water observed off the Compton Glacier in 1963 had now developed into a beach, broken in the centre by a wide outlet from a lagoon that was

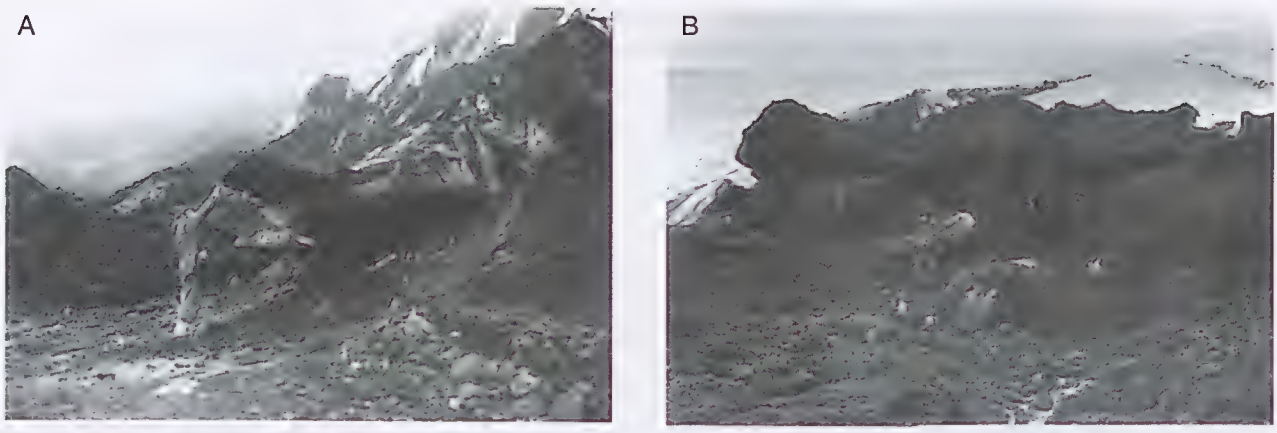

PLATE 1
(A, B) Abbotsmith glacier terminus at Henderson Bluff on 7 February 1971. Both photos show extruded ice slabs, and (B) shows large blocks of fallen ice being overridden by further extrusion. (Photos by G.M. Budd.)

backed by sharp-edged ice cliffs more than 100 m from the beach.

1971

This year's overland circuit of the island revealed continuing retreat of the Stephenson, Brown, Compton, Schmidt and Jacka Glaciers; no further change in the Baudissin and Little Challenger Glaciers; and strong readvance in the Vahsel Glacier and both parts of the Winston Glacier. It also revealed major recession and subsequent readvance in the Abbotsmith Glacier behind Henderson Bluff, which had not been visited since 1954. Details of these changes follow.

Vahsel Glacier

The Vahsel Glacier had developed high and sharp-edged sea cliffs which extended closer to Erratic Point and Cape Gazert, and its general appearance resembled that of 1954.

Abbotsmith Glacier

The Abbotsmith Glacier reaches the sea in high ice cliffs beneath an ice fall between Walsh Bluff and Henderson Bluff, and also has a sloping terminus on the gravel terrace behind Henderson Bluff. In February 1971 it was found that this land-based terminus had retreated 800 m since the previous visit in 1954 but was now re-advancing, with broad ice slabs extruding forward for several metres and curving upwards (pl. 1), in some places as far as the vertical plane. Similar features have been reported at the termini of advancing glaciers in Iceland (Heim 1984, 1985, Humlum 1985).

Winston Glacier

The southwestern stream of the Winston Glacier had advanced a further 200 m since 1965, and its northwestern ice sheet was also advancing: the ice above the bluffs, which in 1963 and 1965 had appeared stagnant, was now thicker, had developed sharply defined and overhanging ice cliffs, and showed considerable avalanche activity. Moreover, an ice tongue on the northwestern side of the central rock promontory had thickened, had spread laterally to cover some of the adjacent bluff, and had advanced into the lagoon on a broad front.

Stephenson, Brown and Mary Powell Glaciers

The Stephenson Glacier had developed a lake, several hundred metres wide, at the point where a large meltwater stream flowed through the Dovers moraine to the northern beach of Spit Bay. The Brown Glacier had retreated another 50 m since 1969. The Mary Powell Glacier above Saddle Point had retreated about 100 m, probably since 1969, and had developed a lake backed by ice cliffs about 6 m in height.

Summary

In summary, the observations from 1963 to 1971 (table 2) showed

- continuous retreat of glaciers on the northeast coast (Stephenson, Brown, Compton and Jacka) throughout all eight years;
- readvance through 1965 and 1971 of the southwestern stream of the Winston Glacier on the southeast coast;
- readvance by 1969 of the north-facing glaciers of Corinthian Bay (Baudissin, Little Challenger), while the Vahsel on the west coast continued to retreat; and
- readvance by 1971 of the Vahsel and Abbotsmith (which had retreated since 1954), and of the northwestern ice sheet of the Winston Glacier, while the Baudissin and Little Challenger showed no further change.

King Penguins

Early history (1858–1929)

King penguins were abundant in the Spit Bay area of Heard Island in 1858 (Crowther 1970), and according to sealers were still present there in 1929 (Falla 1937). Unfortunately the BANZARE party that spent a week ashore in November–December 1929 were unable to visit Spit Bay, and in a thorough search at Southwest Bay they found only a single adult king penguin (Falla 1937).

Continuous ANARE occupation (1947–55)

The first ANARE wintering party found no king penguins at Spit Bay in November 1948, but they did find a small breeding group on the Vahsel moraine in Southwest Bay (Downes *et al.* 1959). These birds raised two chicks, but most of the colony was removed to Australian zoos in February 1949, owing to an unfortunate failure to appreciate the precarious status of the king penguin at Heard Island.

Subsequent observations up to March 1955 have been summarised by Downes *et al.* (1959). There was no further attempt to breed at Vahsel moraine, and only two king penguins were seen on the adjoining beach during a brief visit in March 1960 (Budd, pers. obs.). Wandering individuals and small groups were seen each summer near the ANARE station, and in November 1951 a moulting chick and four other king penguins were seen at Spit Bay. No other evidence of breeding was found at Spit Bay, although field parties had worked there in November in the years 1948, 1949, 1950 and 1951, as well as in July 1951 and December 1954. No breeding birds or even groups of more than a few non-breeders had been seen at other parts of the island, although all parties visiting Spit Bay had walked over the northern beaches and two had continued right around the island. Downes *et al.* (1959) therefore concluded that the occasional birds seen were probably visitors from the large colonies at Kerguelen, 460 km to the northwest, and that the king penguin was no longer breeding regularly at Heard Island.

Summer expeditions (1963–71)

1963

In February and March it was discovered that regular breeding had recommenced (Budd & Downes 1965). More than 100 king penguins were seen, and 23 of them had eggs or chicks. The two largest colonies, with a total of 37 adults and 20 eggs or chicks, were in the tussock grass behind the north and south beaches at Spit Bay (fig. 2). In addition, single incubating birds were seen on the grassy slopes of Vahsel moraine (near the site of the abandoned 1948 colony) and at Saddle Point, and a well-grown chick of the current summer was seen at Skua Beach.

1965

Observations in the eastern half of the island between 31 January and 5 February showed that the breeding population at Spit Bay had more than doubled since 1963 (Budd 1968), with 81 adults and 45 eggs or chicks present in the two colonies. Single incubating birds were seen at Long Beach and Skua Beach. These figures underestimate the breeding population in 1965, because the counts were made three weeks earlier in the laying period than those of 1963.

1969

Counts in mid-March showed a further doubling of the breeding population in the two Spit Bay colonies, to 153 adults and 86 eggs or chicks (Budd 1970b), and a growth of the Vahsel moraine colony to 40 adults and 17 eggs or chicks. Pairs of adults were also seen at Red Island, West Bay and Atlas Cove; Long Beach was not visited. The total count of 199 adults and 103 eggs or chicks indicated an almost fivefold increase in the breeding population since 1963.

1969–70

On 24 October 1969, members of the American wintering party observed a chick in down, accompanied by eight adults, at Red Island; and on 14 February 1970 they counted 54 adults and 19 eggs or chicks at Vahsel moraine (Ben D. Roth, pers. comm.).

1971

The Vahsel moraine colony, counted on 3 and 26 February, had doubled in size since 1969, with 67 adults and 38 eggs or chicks (Budd 1973b). Breeding had also commenced at West Bay, where one bird was found incubating on 8 March; another bird nearby had been incubating a stone since 26 February, presumably because it had lost its egg. No eggs or chicks were seen during searches at Red Island on 31 January and 3 March.

Pattern and rate of increase between 1963 and 1971

Figure 2 summarises the results for Spit Bay and Vahsel moraine (Budd 1975). The north colony at Spit Bay was initially three to four times larger than the south one, but after 1965 the south colony grew more rapidly and the north one more slowly. Consequently the total breeding population at Spit Bay increased almost linearly between 1963 and 1969, at a rate of 11 pairs per year. At Vahsel moraine the pattern of increase paralleled that of the south colony at Spit Bay: both colonies increased exponentially, doubling in size every 2.1 years at Spit Bay south colony and every 1.6 years at Vahsel moraine.

Subsequent observations (1980–93)

1980–87

Observations at Spit Bay and Vahsel moraine in 1980, 1983, 1985, 1986 and 1987, summarised by Gales & Pemberton (1988), showed that exponential population growth was continuing, at much the same rate as in 1963–71. These authors calculated that the breeding population at Spit Bay

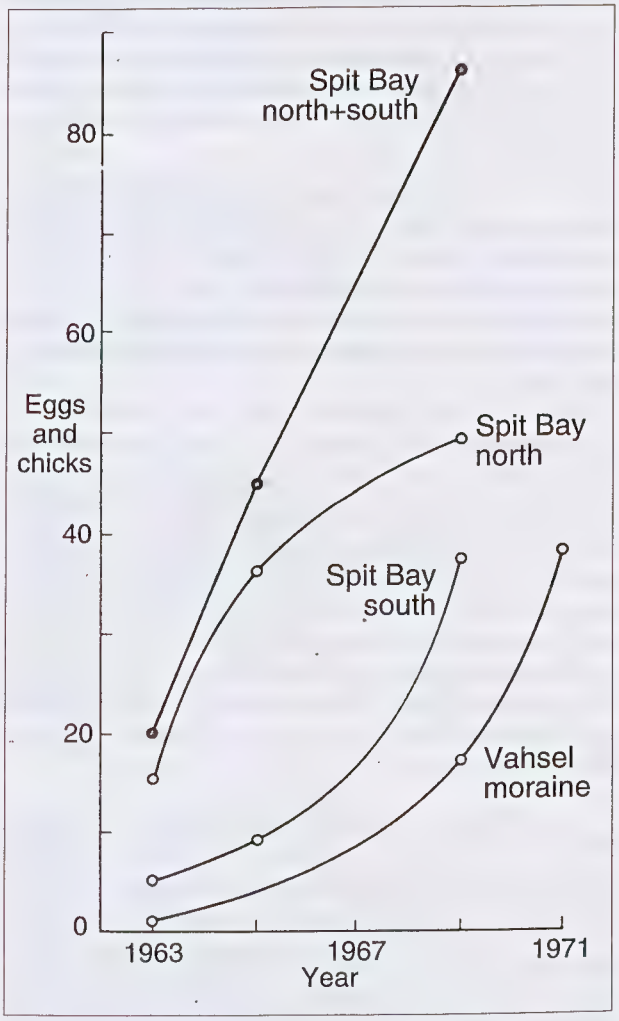

FIG. 2 — *Increases in king penguins from 1963 to 1971 at Spit Bay and Vahsel moraine. (Reproduced, with permission, from Budd 1975.)*

was doubling every 2.7 years at the south colony and every 6.9 years at the north colony. At the Vahsel moraine colony, which between 1980 and 1985 had moved about 1 km to the vicinity of the Schmidt Glacier, there were 175 eggs on 19 January 1987.

1988

At Spit Bay on 16 January 1988 there were 3100 eggs or chicks in the south colony and 215 in the north colony.

1990

In the winter of 1990 a total of 2920 chicks were counted between 22 May and 17 June in four unspecified colonies at the eastern end of Heard Island; 2500 of them were in the Spit Bay south colony (Green & Wong 1990).

1992–93

Counts at the Vahsel moraine (now Schmidt Glacier) colony in February 1992, and at Spit Bay in February–March 1993, yielded a whole-island total of 10 745 breeding pairs, most of which were in the Spit Bay south colony (Green *et al.* 1998). These findings would seem to show that the breeding population at Spit Bay increased threefold in the five years 1988–93.

Breeding success to 1971

Several lines of evidence, summarised below, suggest that in the period 1947–71 few chicks had survived to fledging.

(1) Observations throughout 1969 at Vahsel moraine (Richard Cohen, pers. comm.) appeared to show that only one of the 16 large chicks seen in March had survived to fledging in late November.

(2) "Early breeders" comprised 70% of the breeding adults seen in 1963 and 90% of those seen in 1969 and 1971, although at an established colony in South Georgia they had comprised only 40% (Stonehouse 1960). Early breeders are birds which had not raised a chick in the previous season, either because they had not attempted to breed (as would be the case with newly arrived immigrants) or else had done so and failed.

(3) No chicks of the previous season were ever seen in the late-summer visits (31 January to 17 March) between 1963 and 1971, although at South Georgia and the Crozets they may be seen until early March (Stonehouse 1960, Despin, Mougin & Segonzac 1972). The absence of such chicks at Heard Island, although partly explained by the predominance of early breeders (whose chicks fledge before January), suggested that the chicks of late breeders had all died. This suggestion is consistent with the observation that the single moulting chicks seen at Spit Bay in November 1951 and at Red Island in October 1969 were clearly from early breeders and may have been the sole survivors of whatever eggs had been laid that year.

In explanation of this apparently high rate of breeding failure it was suggested (Budd 1975) that the chicks of small colonies would have difficulty in surviving the Heard Island winter because they would be too few to obtain much benefit from huddling together in the colder weather. It would also be expected that the chicks of late breeders would be more vulnerable to cold than those of early breeders because they would be smaller and less mature at the onset of winter.

Recent findings at Kerguelen and Iles Crozet are consistent with the above observations and their interpretation. Weimerskirch and his colleagues reported that at these islands small colonies of up to 150 pairs of king penguins have produced very few fledglings, or none at all, because of predation by giant petrels on the small huddles of chicks guarded by too few adults (Weimerskirch *et al.* 1989, 1992, Jouventin & Weimerskirch 1990). Weimerskirch *et al.* (1992) concluded that breeding success varies directly with colony size, and that only colonies of more than 200–300 pairs produce chicks that are likely to be recruited later as breeding adults. Southern giant petrels (*Macronectes giganteus*) breed at five places on Heard Island (Downes *et al.* 1959) and were the main cause of chick deaths during the winter months in 1992 (Moore & Robertson 1993), although the colonies of king penguins were by then so large that many thousands of chicks nevertheless survived to fledging.

Habitat preference and distribution

In the first two decades of recolonisation king penguins bred at nearly every beach on Heard Island, usually on the tussock grass (*Poa cookii*) and azorella (*Azorella selago*) some hundreds of metres behind the beaches (Budd 1975). At most beaches they persisted in breeding for a year or two, with no great increase in their numbers, and then abandoned the site. However, a few sites, such as Spit Bay and Vahsel moraine, seem to have proved especially attractive, and at these sites rapid population growth has ensued.

An interesting reversal of habitat preference occurred at Spit Bay in the first decade of colonisation. In 1963 and 1965 the south colony was only one-quarter the size of the north colony (fig. 2), but thereafter population growth accelerated in the south colony and slowed in the north colony, so that by mid-January 1988 (Gales & Pemberton 1988) there were 14 times as many eggs or chicks in the south colony as in the north (3100 and 215 respectively). Moreover, the finding of king penguin bones at a depth of 45–60 cm near the south colony (Green 1990b) would seem to show that this site has been used in former times. Why the king penguins should prefer Spit Bay and Vahsel moraine over other localities, and why they switched their preference from the north to the south colony at Spit Bay, are matters for conjecture, but inspection suggests that the favoured sites are more sheltered than other localities, and at Spit Bay they are sunnier (Budd 1975).

Immigration

The rapidity of the increase in the numbers of king penguins at Heard Island between 1963 and 1971, despite what appeared to have been a high rate of breeding failure, strongly suggested that the population growth at that time was due, at least in part, to a continuous recruitment of immigrants from some other island. This interpretation was confirmed by the finding that between 31 January and 5 February 1965 there were more juvenile king penguins (birds hatched in early 1963) in the eastern half of Heard Island than there had been eggs or chicks in the whole island in 1963 (Budd 1968); and it was later extended by the conclusion (Weimerskirch *et al.* 1989) that small colonies of king penguins can grow only through the immigration of birds from large colonies. No king penguins have been seen at the offlying McDonald Islands (Budd 1972a, Johnstone 1982) or Shag Island (Tremont & Vining 1983), and the most likely source would seem to be the large colonies at Kerguelen (Budd 1968, Weimerskirch *et al.* 1989).

However, Weimerskirch *et al.*'s findings also implied that since about 1980, when the size of individual colonies at Heard Island first exceeded 300 pairs (Johnstone 1982, Gales & Pemberton 1988: table 1), local recruitment from successful breeding in these colonies would have made an increasing contribution to population growth, reducing the relative contribution of immigration.

Fur Seals

Early history (1855–1955)

Fur seals were present at Heard Island in the 1850s but were virtually exterminated by sealing (Gwynn 1953, Ingham 1960), and until 1947 there were no further reports of their presence. Between 1947 and 1955 they were frequent summer visitors, but the largest concentration seen was 50 seals (at Red Island on 17 February 1954) and there was no firm evidence of breeding. Small seals of about 1 m in length were occasionally seen, but they were never in their black natal fur and were never seen to suckle, and it is probable — as the observers usually concluded — that they were yearlings (Gwynn 1953, Ingham 1960).

Summer expeditions (1963–71)

1963

Between 19 February and 8 March — the probable time of maximum numbers (Csordas & Ingham 1965, Shaughnessy & Goldsworthy 1990) — approximately 500 fur seals were ashore: 464 were counted, and there were probably another 20–30 at the unvisited Green Valley (subsequently renamed Paddick Valley), where 26 were counted in 1965 (Budd & Downes 1969). The main concentrations were 131 at Red Island, 118 at Fairchild Beach and 126 at Spit Bay.

Two pups were seen and photographed while suckling. One of them, still in its black natal fur, was at Red Island on 25 February; the other, already moulted, was at Fairchild Beach on 7 March.

The skulls of two adult males were identified by Miss J.E. King of the Natural History Museum, London, as typical examples of *Arctocephalus tropicalis gazella*, the southern race of the Kerguelen fur seal (subsequently reclassified as *Arctocephalus gazella*, the Antarctic fur seal).

1965

Only the eastern half of Heard Island (between the Gotley and Compton Glaciers) was searched, between 31 January and 5 February (Budd & Downes 1969). Although these searches were made 3–5 weeks earlier than in 1963 and the seasonal haul-out would not have been complete, the counts were already slightly greater than in 1963, showing that the population had increased. No suckling was seen on this occasion.

1969

Counts at Red Island, Saddle Point, Fairchild Beach, Skua Beach and Spit Bay between 12 and 16 March showed a sixfold increase since 1963 (from 439 to 2662) that was evenly distributed among the five localities (Budd 1970c). If a similar increase had occurred at the unvisited Green (Paddick) Valley, the total population of the island would have been about 3000 seals.

Three pups, two of them suckling, were seen at the western end of Fairchild Beach, close to the place where suckling was seen in 1963. (This locality, subsequently named "Fur Seal Creek", was the largest breeding site on the island (93 pups) in the summer of 1987–88 — Goldsworthy & Shaughnessy 1989). The pups seen in 1969 had already moulted from their black natal fur, and were accompanied by their mothers, a yearling and a bull. Several more pups were seen at Red Island, making a probable total of six pups for this year.

A plot of the counts made in late February and March at Red Island over the 18 years from 1951 to 1969 (fig. 3) showed that the population there had increased exponentially over this period. When allowance was made for the underestimate, by perhaps 40%, of the maximum population in the early counts of 1965, it was apparent that exponential population growth had also occurred at Saddle Point, Fairchild Beach, Skua Beach and Spit Bay.

1971

Repeated counts at Red Island on 31 January and 1 February, and two more counts on 3 March, yielded a mean value of 948 seals — 39% more than the 683 seals counted in the same place on 18 March 1969 (Budd 1972b). There were about a dozen yearlings, and three black pups which were usually accompanied by their mothers and were seen suckling. One of the pups was already moulting on 1 February, but the other two were still in their black coats on 3 March.

Classified counts during this census showed that 84% of the seals were large bulls more than 1.5 m in length; most of the remainder, of length 1.0–1.5 m, were thought to be immature males. This distribution was similar to that of other herds on the island in 1971 and previous years, and it showed no obvious change between 1 February and 3 March.

Subsequent observations (1980–93)

Counts at most localities in February and March in 1980, 1988 and 1992 yielded whole-island totals of 4500, 9748 and 21 536 fur seals (Johnstone 1982, Goldsworthy & Shaughnessy 1989, Green 1993b). The numbers of pups counted in the whole island in the summers of 1979–80,

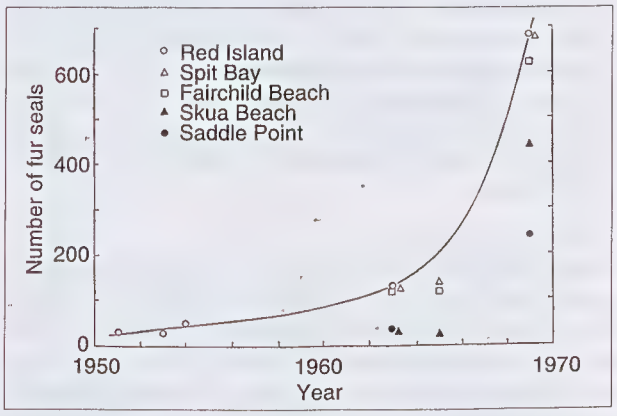

FIG. 3 — *Fur seals on Heard Island at the probable time of maximum numbers (late February and March) 1951–69. Counts made at other times are excluded, except for those of 31 January and 1 February 1965 (which underestimate the maximum numbers that year). The curve is eye-fitted through the points for Red Island. (Reproduced, with permission, from Budd 1970c.)*

1986–87 and 1987–88 were 46, 172 and 248 (Shaughnessy *et al.* 1988, Shaughnessy & Goldsworthy 1990) and the estimated number in 1992–93 was 343 pups (Shaughnessy *et al.* 1998). These results show that both the breeding and the non-breeding populations have continued to increase exponentially.

Habitat preference and distribution

The fur seals at Heard Island appear to have shown a strong preference for localities sheltered from wind. In 1963, almost all were on the lee (the northern and eastern) side of the island, many of them in places that were further sheltered by hills or moraines (Budd & Downes 1969) — in contrast to the Subantarctic fur seal *Arctocephalus tropicalis* at Amsterdam Island, which is reported to prefer the windward coasts (Paulian 1964). Like the fur seals at South Georgia (Bonner 1958, 1968, Boyd 1993) and Marion Island (Rand 1956), the Heard Island seals avoided rocky areas: breeding and non-breeding animals alike occupied the vegetated hills and terraces behind the beaches, sitting or lying on grass tussocks *(Poa cookii)* or among tall stands of Kerguelen cabbage *(Pringlea antiscorbutica).* They amicably shared their habitat with elephant seals and with nesting gentoo penguins (*Pygoscelis papua*), king penguins and giant petrels, although they usually threatened and often charged any men who came near them.

As their numbers increased the fur seals tended to take up localities they had previously avoided, even though there remained room for expansion in the main concentrations — which indeed continued to expand. Such less-favoured (and sometimes less sheltered) localities included Skua Beach, Saddle Point, and the south beach of Spit Bay in 1969 (Budd 1970c); Long Beach, Jacka Glacier and Mt Aubert de la Rue in 1971 (Budd 1972b); and Capsize Beach and Cape Gazert in 1988 (Shaughnessy & Goldsworthy 1990).

Source of the Heard Island fur seals

Initially it was assumed (Gwynn 1953, Ingham 1960) that the Heard Island fur seals were summer visitors from either Kerguelen, 466 km northwest of Heard Island (where they had been abundant before being virtually exterminated by sealers in the 19th century — Allen 1942), or from the McDonald Islands, 54 km west of Heard Island. However, a review of sightings at Kerguelen since 1951 (Budd & Downes 1969) showed that fewer fur seals had been seen there than at Heard Island, and that there was no evidence of breeding.

McDonald Islands

These islands seemed to be a likely source, because they were small, precipitous, inaccessible, and apparently unvisited (Tizard *et al.* 1885). In these characteristics they resembled the Willis Islands, about 10 km west of South Georgia, where a relict population that had survived the sealing era was thought to be the source of the fur seals colonising the other islands of the Scotia Ridge (Bonner 1964, 1968). During the first recorded landing on McDonald Island, on 27 January 1971, it was found that under the eastern cliffs a small sandy beach backed by talus, incompletely inspected and photographed from the cliff-tops above, was occupied by at least 46 black fur seal pups, 68 cows and 32 bulls (Budd 1972a, b). The seals were grouped in seven distinct harems, the largest of which contained 18 cows and 12 pups. Another 53 bulls occupied an adjacent pebble beach.

These observations revealed sharp contrasts in breeding status and habitat between the fur seals of McDonald Island and Heard Island. At McDonald Island at least 68 cows were breeding on one small sandy beach, leaving the adjacent pebble beach to a similar number of non-breeding bulls, whereas at Heard Island an expanding population of 3000 or more, mainly non-breeding bulls, occupied the grassy terraces and hills and, up to that time, had produced only six or so pups each year. It was concluded that the breeding seals at McDonald Island were clearly too few to account for the rapid and continuing increase in the Heard Island population.

A more complete search of McDonald Island, on 12 March 1980 (Johnstone 1982), revealed "up to 100 pups and over 200 others" on the same beaches as in 1971, and showed that there were no other fur seals on the McDonald Islands. The only other potential local source of fur seals was the precipitous Shag Island, 10 km north of Heard Island, but the first recorded landing, on 26 January 1983, showed that there were no fur seals on the island (Tremont & Vining 1983).

Kerguelen

The first breeding colony of fur seals to be reported from Kerguelen since the 19th century was discovered in 1982 at Ile de Croy, one of the Iles Nuages group 20 km northwest of the northern tip of Kerguelen, where geologists found "a breeding colony of about 1,200 animals" (Jouventin *et al.* 1982). A biological survey from 17 November to 14 December 1984 revealed "some 1,500 breeding females" and a total estimated population of "over 5,000 animals" (Jouventin & Stonehouse 1985); a further visit in late summer 1994 yielded a figure of "about 1,900 pups" (Cherel *et al.* 1997). This colony was considered too small to have provided the influx of summer visitors at Heard Island (Shaughnessy & Goldsworthy 1990).

South Georgia

Other breeding colonies may eventually be discovered among the numerous islands of the Kerguelen archipelago. However, the sighting at Red Island in March 1971 of an anomalous pale-coated fur seal raised the possibility that the crowded and expanding colonies at South Georgia (Bonner 1968) might be the source of the fur seals at Heard and McDonald Islands (Budd 1972b). Pale coats occur in about 0.1% of the fur seals at South Georgia and the South Orkney Islands, and the apparent absence of this characteristic from islands outside the Scotia Ridge suggested (Bonner 1964, 1968) that the fur seals of this region may be derived from a single parent population, probably that of South Georgia. Although Bonner (pers. comm.) considered, and recent photographs confirm, that the Heard Island seal was less pale than its counterparts at South Georgia, its presence was nevertheless suggestive, for Csordas (1962) and several later authors (summarised in Shaughnessy & Goldsworthy 1990) have reported instances of fur seals moving over long distances. Boyd (1993), summarising the results of recent studies of the Antarctic fur seal at all its breeding sites throughout the Southern Ocean, noted that several authors have recognised that many of the fur seals probably derive from the South Georgia population. The results of current genetic studies will clearly be of great interest.

CONSEQUENCES

Glacier recession has exposed substantial areas of ice-free terrain, has created several lakes and large coastal lagoons, and has caused changes in coastal currents and sediment transport. These have resulted in severe erosion of some beaches (resulting in the loss of sealers' relics of archaeological value), broadening of other beaches, and changes in orientation of the Spit at the east end of the island (Allison & Keage 1986, Green 1998). Vegetation has colonised ground newly exposed by retreating glaciers (Scott 1990), while plant distributions elsewhere have changed and new species (e.g. *Poa annua*) have appeared, apparently as a result of animal disturbance and warmer temperatures (Scott 1989, 1990). Similar effects on vegetation have been observed at Kerguelen, where recently deglaciated areas have been colonised by the introduced grass *Poa annua* as well as by the native grass *P. kerguelensis* (Frenot *et al.* 1997), and at Marion Island, where warmer temperatures are causing complex changes in nutrient cycles (Smith & Steenkamp 1990).

A potential future dilemma for conservation and management is posed by the expanding populations of king penguins and particularly fur seals at Heard Island, which have already caused substantial damage to tussock grass (*Poa cookii*) and Kerguelen cabbage (*Pringlea antiscorbutica*) (Scott 1990), and presumably to other vegetation. The dilemma has been well articulated by Bonner (1985) and Smith (1988, 1990). Although manuring by seals and seabirds constitutes an important source of nutrients for terrestrial ecosystems (Smith 1978), the recovery of fur seal populations to levels probably higher than they were before exploitation is causing widespread and perhaps irreversible damage to lowland vegetation at South Georgia (Bonner 1985) and the South Orkney Islands (Smith 1988, 1990, 1997). At Bird Island on South Georgia, trampling by fur seals and pressure from their lying on tussocks have destroyed large areas of tussock grass (*Poa flabellata*) and Antarctic hair grass (*Deschampsia antarctica*), leading to severe erosion of soil and peat, and have deprived six species of birds of breeding habitat and exposed them to predation by skuas (*Catharacta lonnbergia*). In addition, disturbance by fur seals may have deterred some young wandering albatrosses (*Diomedea exulans)* from breeding in their natal areas (Croxall *et al.* 1990). At Signy Island (South Orkneys), the increase in fur seals from "a few dozen" in the early 1970s to 20 500 in 1994/95 has caused "widespread devastation" in most lowland terrestrial and freshwater ecosystems (Smith 1988, 1990, 1997). Trampling and the toxicity of excreta and "fur wash" have eradicated extensive communities of mosses and lichens, killed or damaged grasses, caused eutrophication of freshwater lakes, disturbed or eroded lake sediments and moss banks 3000–7000 years old, and destroyed several colonies of giant petrels and Antarctic terns (*Sterna vittata*).

CAUSES OF THE OBSERVED CHANGES

Glaciers

Possible causes of the observed glacier fluctuations include geothermal heat from volcanic activity, and climate change.

Volcanic activity

Observed activity to 1971, summarised by Budd & Stephenson (1970), included a major eruption in 1910 (Padang 1963), a flow of incandescent lava near the summit of Big Ben in 1950 — which may have been responsible for long trenches observed beside the upper Abbotsmith and Gotley Glaciers in December 1954 — and intermittent fumarole activity at various levels on the southwestern slopes between 1949 and 1954. However, by February 1963 the trenches had disappeared; crevasse stratigraphy at the 2100 m level gave no indication that any ash eruptions had occurred for many years; and the summit crater showed only fumarole activity when it was visited for the first time in 1965 (Temple 1966). It was concluded (Budd & Stephenson 1970) that such intermittent, minor and localised volcanic activity could not explain the widespread glacier retreat that had occurred since 1955. This conclusion has been endorsed by subsequent studies (Allison & Keage 1986, Ruddell & Allison 1998); although volcanic activity has intensified in recent years (Williams & Duhamel 1986, Green 1993c), numerical modelling (Williams 1998) suggests that volcanic activity this century has had a negligible influence on the dynamic behaviour and mass balance of the Heard Island glaciers.

Climate change

Air temperature

Annual mean air temperature at Heard Island increased by 1.8°C between 1948 and 1951, and in 1954 was still 1.3°C higher than in 1948 (Budd & Stephenson 1970). Similarly, at Kerguelen the mean air temperature throughout the 1950s was 1.3°C higher than the 30-year mean for 1902–31 (Budd & Stephenson 1970); it then decreased by about 0.8°C in the early 1960s, rewarmed by 1.3°C between 1964 and 1982, and thereafter remained steady until at least 1991 (Radok & Watts 1975, Allison & Keage 1986, Frenot *et al.* 1993). These changes in air temperature were accompanied by a steady rise in the sea-surface temperature between latitudes 30°S and 50°S, which increased by about 1.0°C from the 1930s to the 1980s (Allison & Keage 1986: fig. 8).

The timing, magnitude and direction of the above fluctuations in air temperature seem adequate to explain the accompanying glacier retreat and readvance of the 1950s and 1960s at Heard Island and Kerguelen, and the steady retreat that has subsequently occurred at both islands (Budd & Stephenson 1970, Allison & Keage 1986, Frenot *et al.* 1993, Garvin *et al.* 1999). It is clear that the glaciers of Heard Island are sensitive indicators of regional climate change. Their sensitivity is further demonstrated by the asynchronous timing of the readvances between 1963 and 1971, which presumably was due to interactions between changes in air temperature (and perhaps precipitation and cloud cover) and the individual glaciers' aspect, topography and altitude range (Ruddell & Allison 1998).

Causes of changes in air temperature — atmospheric and oceanic circulation

Loewe *et al.* (1952) suggested, on the basis of sealers' records from the 1850s, that the wind regime at Heard Island and Kerguelen had changed over the past century. Subsequently, Radok & Watts (1975) analysed synoptic surface-weather charts for the period 1949-64, and concluded that above-average air temperatures and glacier recession at Heard Island and Kerguelen had occurred at a time when more low-pressure systems ("cyclones") were passing Heard Island on its southern side than on its northern side, and that the reversal of this distribution in the 1960s was accompanied by the cooler temperatures and glacier readvances observed at that time. However, a subsequent extension of this analysis to cover the period 1972–81 (Allison & Keage 1986) showed that the northerly cyclone paths had persisted although air temperature had once again increased. This finding, although reversing the relationship between cyclone paths and air temperature reported by Radok & Watts (1975), nevertheless confirmed that there had been a "strong and persistent" shift in atmospheric circulation between 1950 and 1980 (Allison & Keage 1986).

Similar changes in circulation have been inferred at other islands. At Marion Island, Smith & Steenkamp (1990) reported a strong correlation between air and sea-surface temperatures, which between 1968 and 1985 had increased by 1.6° and 1.2°C, respectively, and attributed these changes to changing atmospheric and oceanic circulation patterns in the region. Likewise, at South Georgia, Gordon & Timmis (1992), analysing synoptic records of atmospheric pressure, attributed rising air temperatures and glacier recession since about 1950 to regional changes in atmospheric circulation. These inferences would seem to be supported by the recent finding (de la Mare 1997) that the summer sea-ice edge around Antarctica abruptly moved southwards by 2.8° of latitude between the mid 1950s and early 1970s and then stabilised in its new position.

King Penguins and Fur Seals

Possible causes of the observed recolonisations include recovery from past exploitation, climate change, and an increased food supply.

Recovery from past exploitation

Although the circumpolar increase in king penguins and fur seals over the past 40 years (Conroy & White 1973, Croxall *et al.* 1988, Jouventin & Weimerskirch 1990, Boyd 1993, Guinet *et al.* 1996) shows that they clearly are recovering from past exploitation, such exploitation ended at different times among the numerous islands concerned, and recovery from it therefore seems unlikely to be the sole explanation for the present increase at Heard Island.

Climate change — terrestrial effects

The observation that recolonisation of Heard Island by king penguins and fur seals coincided with a period of major glacier recession naturally raised the question whether regional warming might have been partly or wholly responsible for all three phenomena (Budd & Downes 1965, 1969). The available information about the microclimate of king penguin colonies at Heard Island and elsewhere (Budd & Downes 1965), and their apparently high rate of breeding failure at Heard Island between 1963 and 1971, appeared to support an earlier suggestion (Downes *et al.* 1959) that the Heard Island winter might be too severe for king penguins to raise their chicks. Moreover, the preference of both king penguins and fur seals for sheltered and sunny habitats seemed to show a degree of sensitivity to cold that might previously have discouraged them from colonising Heard Island.

However, evidence to the contrary was provided by historical records of king penguins and fur seals on Heard Island in the 19th century, when the glaciers were not in recession; by the presence of large breeding colonies of fur seals on colder islands such as the South Shetlands, both in the 19th century (Bonner 1968) and in recent decades (Bonner 1964, Boyd 1993); and by the lack of any obvious effect of the lower air temperatures during the 1960s (Budd 1975). On balance, it appeared unlikely that warmer temperatures on shore had influenced the recolonisation of Heard Island by king penguins and fur seals.

Food supply

The demonstrated importance of immigration to the increase in king penguins and fur seals at Heard Island, and the circumpolar distribution of similar increases at other islands, suggested that the main cause of recolonisation might lie as much with conditions at the migrants' parent colonies, or in the sea, as with conditions at Heard Island itself. It was therefore suggested (Budd & Downes 1965, 1969, Budd 1975) that the increase was probably a response to an increase in the availability of food, consistent with the suggestion (Sladen 1964) that a concurrent increase in Adelie and chinstrap penguins (*Pygoscelis adeliae* and *P. antarctica*) might be due to a surplus of krill resulting from the depletion of whale stocks by over-fishing (Mackintosh 1970).

Reduced competition from whales

Subsequent studies of Antarctic marine ecosystems (e.g. Croxall 1992, Guinet *et al.* 1996) have generally supported Sladen's suggestion, while also identifying additional causes of population changes in seabirds and seals. Guinet *et al.* (1996) drew attention to the paradox that although the depletion of whale stocks ought to have mainly benefited predators of crustaceans (such as macaroni penguins, *Eudyptes chrysolophus*), in fact the highest population growth rates at Crozet and Kerguelen have been in king penguins and fur seals, which in this region feed mainly on pelagic lantern fish (myctophids). In explanation the authors note that Antarctic and Subantarctic myctophids are themselves major consumers of crustaceans, and they suggest that myctophid stocks may have been enhanced by the biomass of crustaceans freed by the removal of baleen whales.

Changes in atmospheric and oceanic circulation

Guinet *et al.* (1996), in a summary that applies equally well to Heard Island, attributed recent major changes in the populations of seabirds and seals at Crozet and Kerguelen to multiple factors, which include not only recovery from past exploitation and reduced competition from whales but also long-term fluctuations in the abundance and/or availability of the main prey species. Changes in atmospheric and oceanic circulation are major influences on such fluctuations in prey species (Priddle *et al.* 1988, Croxall 1992, Murphy & King 1997). Their effects on ice cover near the Antarctic Peninsula have been linked to population changes in Adelie and chinstrap penguins (Fraser *et al.* 1992); and El Nino–Southern Oscillation (ENSO) events have been associated

with changes in the populations of fur seals on Crozet, Amsterdam, and St Paul islands (Guinet *et al.* 1994), with reductions in survival and breeding success of seals and seabirds at South Georgia (Croxall *et al.* 1988, Priddle *et al.* 1988), and with fluctuations in the breeding population of elephant seals (*Mirounga leonina*) in the South Shetland Islands (Vergani & Stanganelli 1990).

Similar mechanisms, acting over a period of decades rather than years, may explain the changes of the past 50 years in the climate, glaciers, and animal populations of the South Indian Ocean, and possibly of the entire Subantarctic region. The strong and persistent shift in cyclone paths near Heard Island (Radok & Watts 1975, Allison & Keage 1986), and the southward movement of the summer sea-ice edge around Antarctica (de la Mare 1997), may both reflect long-term changes in atmospheric and oceanic circulation which have altered marine ecosystems in a way that has improved the food supply of king penguins and fur seals. If this suggestion is correct, then the concurrent changes of the past 50 years in the Heard Island glaciers, king penguins and fur seals may indeed have had a common origin.

CONCLUSIONS

The Heard Island glaciers have proved to be sensitive indicators of climate change in the Southern Ocean, and of the interactions between climate and glacier topography. The island's recolonisation by king penguins and fur seals is attributed mainly to an improved food supply which may itself, like the glacier recession, be a response to changes in atmospheric and oceanic circulation. Glacier recession and its consequences are changing the island's coastline, and the expanding populations of king penguins and fur seals are damaging the vegetation. All these phenomena, occurring as they do in an island with a hitherto undamaged ecosystem and no introduced predators, clearly warrant continuing study.

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ON THEIR OWN: TOWARDS AN ANALYSIS OF SEALERS' SITES ON HEARD ISLAND

by Angela McGowan

(with nine text-figures and six plates)

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Heard Island is possibly the remotest speck of land on the Earth. It was only in the 1850s that the human race finally reached this most isolated of places. For the next 30 years gangs of hunters established themselves on the isolated beaches of Heard Island to slaughter the wildlife for their oil and furs and ship the products to markets half-way around the globe. The material culture remains of these enterprises survive on the beaches, comprising the remnants of the seal-hunters' camps and their processing sites. These sites provide evidence of 19th-century sealing technology and the diverse ethnicity and cultural composition of the sealing gangs. Remains of sealers' camps are found on many of the beaches around Heard Island but are now extremely threatened by coastal erosion. Many of these sites include tryworks situated on raised stone platforms, a form of sealing architecture thought to be unique to Heard Island.
Key Words: cultural heritage, archaeology, Heard Island, sealing, industrial archaeology.

PREAMBLE

This paper is a more detailed version of one I gave at the Heard Island workshop held at the Australian Antarctic Division from 29 June to 1 July 1998 (McGowan 1998, Selkirk 1998). My objective was to present something of the variety of historic sealers' sites on Heard Island and to demonstrate some of the complexity and potential of the archaeology of the sealing industry. My unashamed purpose was to encourage the Antarctic Division to manage the cultural resources on Heard Island pro-actively while the resource still exists, and to give a high priority to supporting a serious programme of archaeological research in the coming 1999/2000 field season. These sites are highly threatened by and vulnerable to both coastal erosion and the wildlife. What is left of this unique record of 19th-century life will not survive for much longer. The site information in this paper is based on my visit to Heard Island some twelve years ago in 1986. Other papers given at the workshop will show that the sealing beaches have eroded so much that some site locations may now have disappeared and others are severely threatened (Green 1998, and herein, p. 27). It would not be an exaggeration to describe the situation as a crisis which demands an adequate response. In my opinion, the highest priority would be to undertake high-quality archaeological research targeted at the most vulnerable sealers' sites.

INTRODUCTION

At 53°S in the Southern Ocean, Heard Island is arguably the most remote speck of land in the world. It is over 4000 km from Fremantle and about the same distance from South Africa. The nearest land is the bleak Kerguelen Islands group about 466 km to the northwest.

Heard Island is about 40 km long by 26 km across and is dominated by a 2750 m high active volcano, Big Ben — the highest mountain in Australia (and still growing!). About 80% of the island is covered with ice, and there is considerable evidence that, in the 19th century, the ice cover was even more extensive (Allison & Keage 1986, Budd 1998). Today, many of the glaciers terminate in icy lagoons separated from the sea by low, stony terminal moraines, which give access from one beach to another. A hundred years ago, most glaciers came down to the sea, terminating in huge ice cliffs and effectively isolating the sealing beaches as pockets of settlement. These beaches are where the seals congregate, and where the sealers who hunted them lived and worked.

Communication across the glaciers was difficult and hazardous. In this paper, I argue that isolation is a recurring theme for understanding the archaeology of Heard Island:
– the isolation of Heard Island itself,
– the social isolation of various ethnic groups in the sealing gangs (apparent from the historic sources and perhaps potentially identifiable in the archaeological record),
– the isolation of the product from its market.

The most abundant species of seal is the Southern Elephant Seal, *Mirounga leonina,* which the sealers hunted for oil. Also common is the Antarctic Fur Seal, *Arctocephalus gazella,* which may have been a minor prey species (Shaughnessy *et al.* 1988).

General descriptions of the geography and natural history of Heard Island were given by Keage (1981), Shaughnessy *et al.* (1988) and other papers in this publication. A definitive comprehensive history of the sealing industry on Heard Island has not yet been written. Neither was this an objective of this archaeological survey. Such a project would complement and provide an essential context for understanding the significance of the material culture remains (the archaeology) of the island. A number of works deal with various aspects of this history, and the historical summary presented here draws largely on these works (Bertrand 1971, Busch 1980, 1985, Downes 1996, Richards 1981, Roberts 1950).

Heard Island was apparently discovered and exploited quite late in the history of the southern sealing industry. The Kerguelens were discovered in the 1770s and have been exploited for seals since then. The discovery of Heard Island occurred much later, although the exact date is a matter of controversy (Bertrand 1971: 228–229, Roberts 1950: 580, Shaughnessy *et al.* 1988). The first sightings

may have been kept secret to protect commercial interests. The discovery was reported by Captain John Heard in 1853, followed by the first recorded sealing expedition in 1855. Sealing continued vigorously and unabated for about 30 years until the 1880s (Downes 1996). One firm, the South African based Kerguelen Whaling and Sealing Co., resumed sealing during the 1920s (Busch 1980: 125, Roberts 1950: 588). It was at this time that the British Admiralty commissioned some sealers to build a small wooden hut, the Admiralty Hut, at Atlas Cove (Keage 1981: 14).

Most sealing enterprises on Heard Island were American. They operated out of New London, Mystic and other New England ports, and were based primarily at the Kerguelen Islands. During these expeditions, captains would cross to Heard Island where they would drop off one or more gangs of sealers for the summer. In many cases the gangs stayed a full year, so that they could continue sealing while their ship took home a cargo of oil (Busch 1985: 171–172).

The ships rarely stayed long, due to the difficulty of finding a safe anchorage. The weather at Heard Island is extremely unpredictable and changeable. Access to the sealing beaches around Heard was difficult — a dangerous trip through the surf or a traverse across a crevasse-ridden glacier. Mostly the gangs stayed where they landed — they were on their own.

In this paper, I look at the distribution of the suite of sites associated with the 19th and early 20th century sealing industry, and at the differences between sites at various locations around the island. This analysis is based on the fieldwork undertaken in 1986/87, when over 20 sites were recorded on beaches around the eastern, southern and northwestern ends of Heard Island. I also argue that a number of formal differences can be identified between the remains found at the eastern and those at the northwestern ends of the island. All the eastern sites show such similarities of form that they are almost certainly from the same or related operations, and probably date from the last sealing expedition in the 1880s. Here, there seems to have been a distinct separation between living and work areas.

Figure 1 shows the locations of sealers' settlements mentioned in this paper.

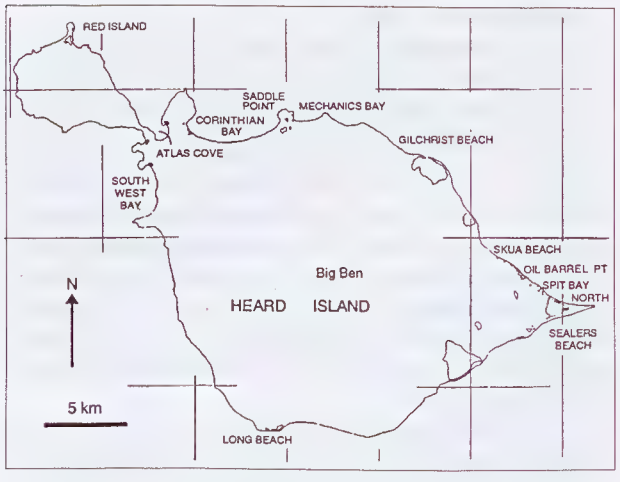

FIG. 1 — Location of sealing sites recorded at Heard Island 1986–87.

Documentary sources

Historical documentation relating to the sealing industry on Heard Island consists of captains' logs and memoirs and 19th-century American seal fishery statistics. Most of these are located in America and available to Australian researchers only through various secondary sources (Busch 1980, 1985, Clark 1887, Downes 1996, Nunn 1850, Richards 1981, Roberts 1950). One notable exception is the memoirs of Captain James Robinson, a Tasmanian sealer of American descent, who led an expedition to Heard Island for Dr W.L. Crowther in 1858. His memoirs are held by the State Library of Tasmania (Crowther 1940, 1943, 1970, Robinson n.d.). Also available are the published accounts of the *Challenger* scientific expedition which visited Heard Island in 1874, making contact with a sealing gang stationed there (Campbell 1876, Moseley 1879, Thomson & Murray 1885).

THE ARCHAEOLOGICAL DATA

Following a detailed and carefully documented report of sealing remains by biologist Harry Burton in 1985 (Burton & Williams 1985), my colleague, Estelle Lazer, and I spent two months on Heard Island in the summer of 1986–87 as members of an ANARE expedition (Ledingham 1987, McGowan 1988). Our major project was to conduct a preliminary inventory survey of sealing sites and make appropriate management recommendations (Lazer & McGowan 1987, 1989, McGowan 1988, McGowan & Lazer 1988).

We identified four different types of sealing sites: stone platforms, hut footings or ruins, occupied caves and barrels. Two other site types have also been recorded by previous and subsequent expeditions. These were graves at South West Bay and Corinthian Bay (Burton & Williams 1985: 46, Robb 1988: 155) and an occupation pit at Corinthian Bay (Robb 1988: 155). In addition, there were many isolated sealers artefacts scattered across the beaches, including pieces of trypots.

Stone platforms

Elevated stone work platforms were constructed at a number of locations on the southern and eastern beaches. We found them at several Spit End beaches and at Long Beach. Artefacts found on and around the structures confirmed that they date to the first sealing period in the second half of the 19th century. As far as my colleague and I are aware, these stone platforms are a form of sealing architecture unique to Heard Island. Nothing like them is reported from Marion Island or Prince Edward Island (Cooper & Avery 1986), Macquarie Island (Townrow 1989) or the sealing islands around Tasmania, such as the Ile de Phoques (pers. obs.), Preservation Island and the other Bass Strait Islands (pers. obs., Harris 1988).

The platforms were constructed from large beach cobbles built into subcircular mounds, ranging in size between 4 m and 17 m across. Typically these mounds are located above the shoreline on flat coastal plains heavily dissected by seal wallows. The wallows consist of deep boggy patches between elevated clumps of vegetation such as tussock grass or *Azorella*. Evidently the stone platforms were built to elevate sealing activities above the general level of the wallows and

were about half a metre high. Most of the platforms have themselves been dissected by seal wallowing, especially around their edges, and in some instances it was difficult to determine a boundary for the edge of a mound, particularly where rocks occur naturally in the area. The function of the platforms was apparently as working platforms and the more intact ones supported remains of tryworks including trypots, flensing floors and other equipment.

Five mounds had sealing artefacts associated with them. The largest of the mounds, at Spit Bay North, had substantial remains of a tryworks (fig. 2, pl. 1) including four surviving trypots and pieces of a fifth, a fire-box made of bricks and iron beams, a scrap blubber press and the remains of a large flensing floor. Two other mounds in the Spit End region had trypots and/or other tryworks equipment on or immediately adjacent to them.

These were at Sealers Beach, where the mound also incorporated bricks and had trypots and a copper oil tank (fig. 3, pl. 2), and at Trypot Beach, which had a trypot. One other mound at Spit Bay North had associated with it a wooden flensing floor (fig. 4) and a blubber skimmer, mentioned by Burton & Williams (1985: 50) but not recorded by us in 1986–87. Another had several sealing tools. Two mounds had no diagnostic artefacts found with them. These were the smallest mound at Spit Bay North and the mound at Long Beach. The location of all these mounds close to the shore and exposed to the unhindered winds suggests that these mounds were sited for working convenience rather than domestic comfort.

It is not clear what sort of structures were built on the platforms at Spit End, but they were most probably made of wood. Two platforms supported wooden floors, built from an apparently random selection of beams, planks and unworked timber. Another platform had what may be either the remains of a floor or part of a collapsed wall. Timber pieces of various shapes and sizes found lying alongside each other have been interpreted as floors. Groups of similar planks or boards found lying in disarray have been interpreted as collapsed walls. The large tryworks at Spit Bay North had two wooden uprights between the fire-box and the wooden floor, and these may have contributed to the support of a roof of some kind. There are two illustrations drawn in 1883 of an 1860 expedition, which show sealers working at the Spit and rolling barrels towards a tryworks (almost certainly the Spit Bay North site) sheltered under a roof supported by four upright posts and with open sides (reproduced in Downes 1996: 61, 87). Despite the lack of any substantial evidence for walled structures, it is hard to imagine that the sealers did not erect some protective windbreaks on their working platforms.

The one exception to the above general description and possible interpretation was the hut mound at Long Beach, a stone platform supporting a hut with stone footings. Its location in the wallows implies the mound initially had an industrial function (although no remains of tryworks equipment were noted to support this), with domestic functions being accommodated in the small cave on the moraine. Later, it was probably used as the platform for a domestic hut.

Barrels

Barrels and barrel pieces are widespread across the beaches of Heard Island. The distribution of isolated barrel pieces is probably the result of dispersal by the wind rather than representative of the original location of barrels. Where barrels are found eroding out of the ground or where there is a group of iron components, the site is probably at its original location.

Barrels were used to contain food and other goods such as coal, as well as to store and transport blubber and oil (Bertrand 1971: 249, Campbell 1876, Moseley 1879: 229). Therefore, their presence is not specifically diagnostic of either industrial or domestic activities.

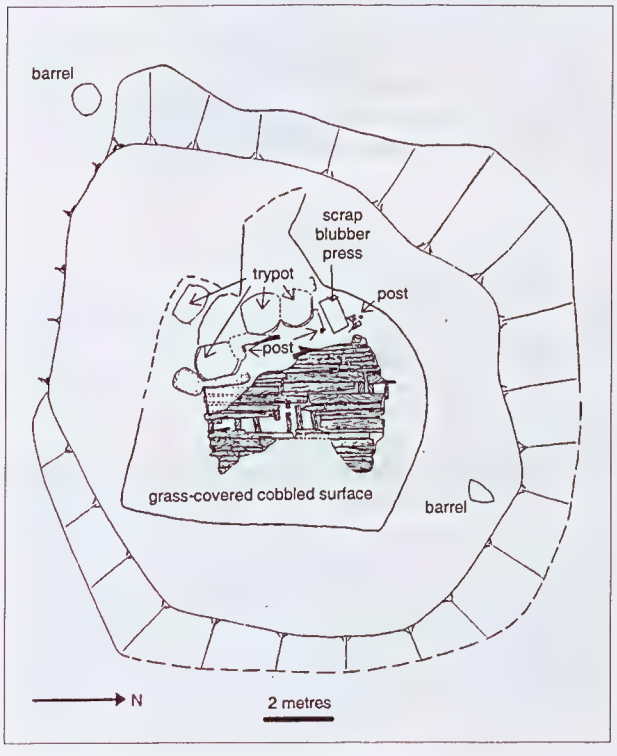

FIG. 2 — Plan of tryworks mound at Spit Bay North, Heard Island 1986–87.

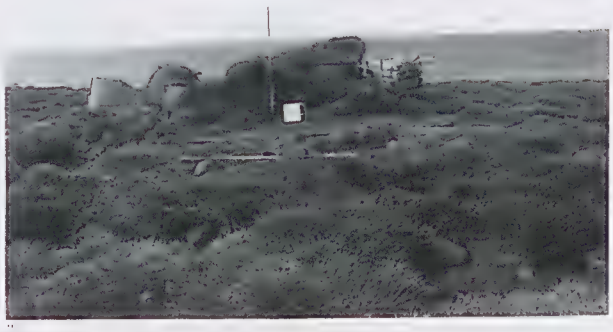

PLATE 1
Spit Bay North tryworks mound.

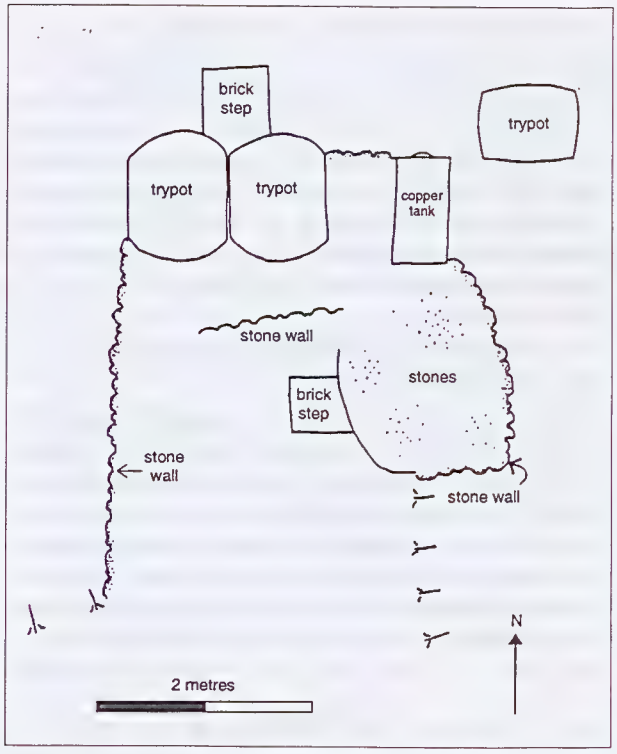

FIG. 3 — Plan of tryworks at Sealers Beach, Heard Island 1986–87.

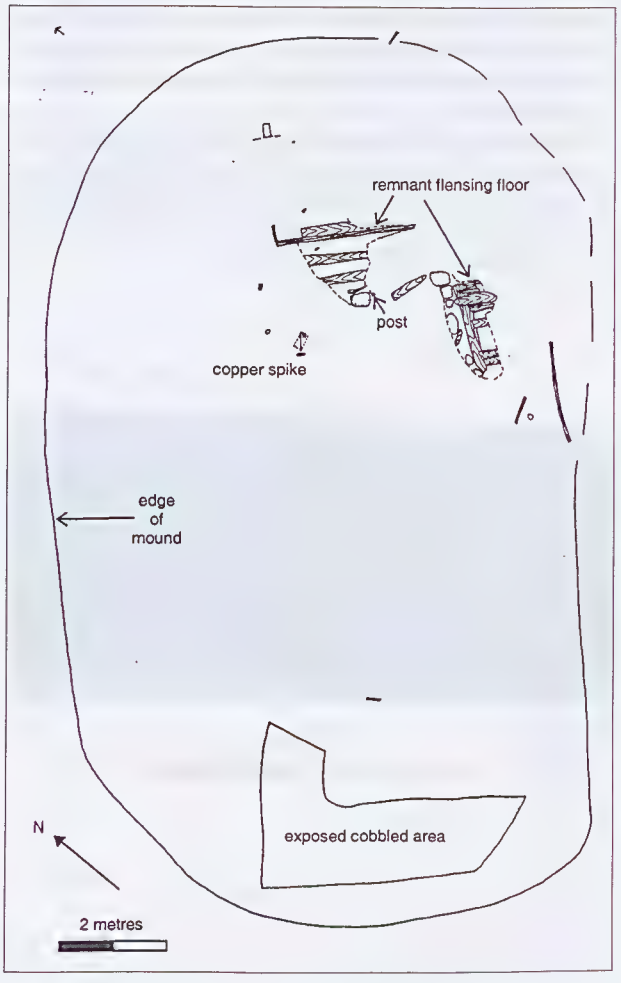

FIG. 4 — Plan of stone platform at Spit Bay North, Heard Island 1986–87.

PLATE 2
Sealers Beach tryworks mound.

Two sites may be cooperage sites, where barrels were put together, although in both cases the evidence is inconclusive. One of these, at Spit Bay North, contained a large collection of coopering iron, sealing tools and ships' dunnage, which suggests that a cooperage and tryworks had been in this area. No structure was found in the vicinity, although Burton & Williams (1985: 51–52) reported an extensive scatter of clay smoking pipes nearby. At Sealers Beach, a small brick and stone structure with associated barrel components may have been the cooperage for this settlement.

There were two barrel caches. The largest, at Oil Barrel Point, comprised 35 barrels (in 1986) lying on their sides in two rows supported by lines of rocks (fig. 5, pl. 3). A small excavation of five barrels showed that they contained variously: congealed blubbery oil, dismembered penguin pieces in solidified oil and whole giant petrels (which may have fallen in while trying to eat the oil). The casks appeared to be stacked ready for taking off. They are probably best interpreted as the last cache of the first sealing period, abandoned for some reason presumably by the last sealers to work that end of the island.

Red Island had a small cache of six barrels sitting end up. The date of this site is unclear.

A number of barrels and barrel pieces have been found at Atlas Cove. Some of these bear the stencilled marks of the 20th-century Kerguelen Whaling and Sealing Company.

Hut ruins

Stone hut ruins have been found on virtually all the sealing beaches. There is a variety of hut styles and evidence of the use of a variety of materials.

The hut at Long Beach has already been mentioned as it was the only one to be built on a platform (fig. 6, pl. 4). The hut was rectangular and smaller than the mound. Stone footings survived to a height of 0.75 m, together with four upright wooden posts and the remains of six others. There was also evidence for the use of turves in the construction. The hut was probably roofed with a sail or with seal skins as the two largest upright posts were peppered with a variety of copper and iron nails which may have held the roofing material in place. The quantity and variety of nails may be the result of re-covering the roof, perhaps many times, with new material as the old one wore out. The probable appearance of this hut has been reconstructed

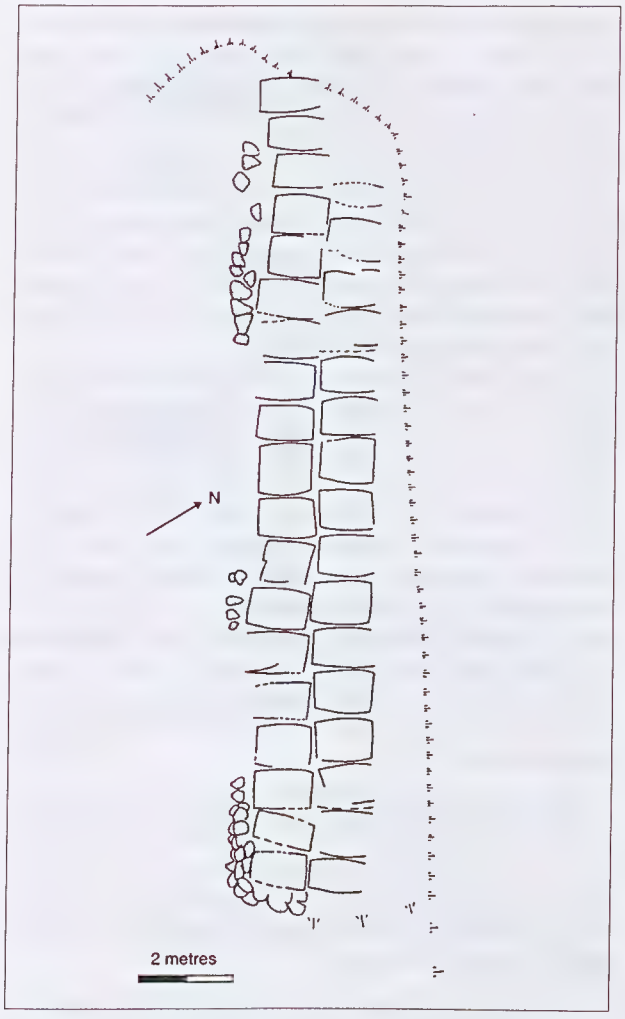

FIG. 5 — Detailed plan of barrels at Oil Barrel Point, Heard Island 1986–87.

PLATE 3
Recording the barrel cache at Oil Barrel Point (see also fig. 5).

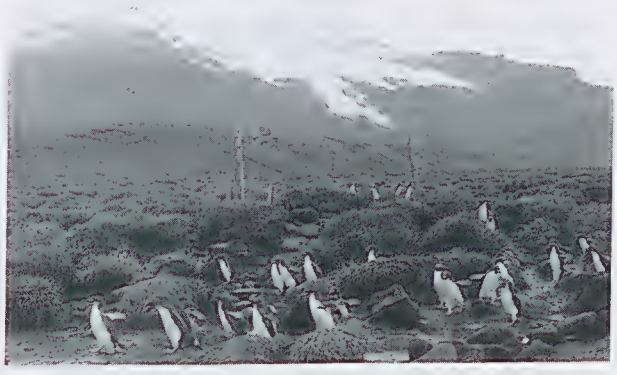

PLATE 4
Hut remains at Long Beach.

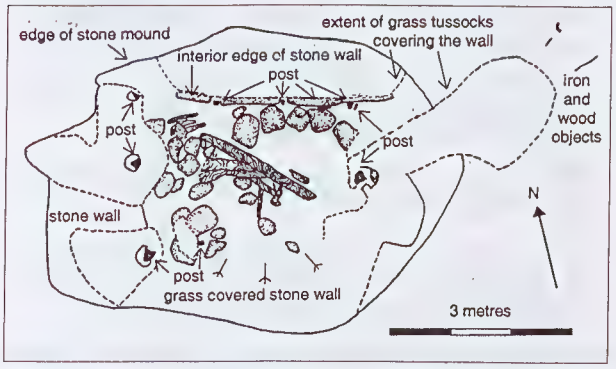

FIG. 6 — Plan of hut site at Long Beach, Heard Island 1986–87.

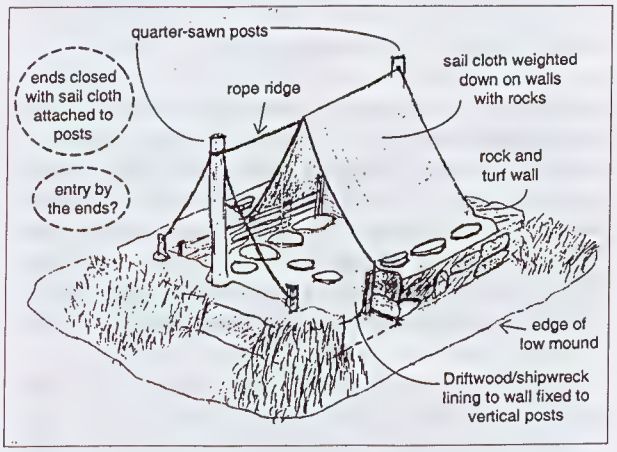
quarter-sawn posts
ends closed with sail cloth attached to posts
rope ridge
sail cloth weighted down on walls with rocks
rock and turf wall
entry by the ends?
edge of low mound
Driftwood/shipwreck lining to wall fixed to vertical posts

FIG. 7 — Architect's reconstruction of the sealers' hut at Long Beach, cut away to show the construction and interior.

from our field notes by Simon Hayman of the Department of Architectural Science at the University of Sydney and is shown in figure 7.

There is documentary evidence for the use of sail and skin roofs by 19th-century sealers elsewhere on Heard Island (Crowther 1943: 553). The erection by sealers of turf-walled huts roofed with sails and skins or grass thatch on wooden or whale bone rafters is well documented on the Kerguelen Islands and on Heard Island (Clark 1887: 436, Nunn 1850: 87, 97, 121, 162).

There is some contradiction in the documentary sources as to whether or not seals were actually slain and processed at Long Beach. Moseley (1879: 227), the naturalist with the 1874 *Challenger* expedition, reported that he was told by sealers at Corinthian Bay that seal killing and processing did not take place on Long Beach, but that men lived there in order to drive seals back into the water so they would

haul up in a more convenient place. Clark (1887: 421) also stated that men were sent over from the other side of the island to live here in order to drive off the seals. Thomson & Murray (1885: 377) in the official narrative of the *Challenger* expedition confirmed that this activity took place but stated also that blubber was collected at Long Beach and transported over the glaciers to Spit Bay. The location of the site amongst the wallows, together with the fact that some effort has gone into building a platform here despite the well-known existence of a small but habitable cave nearby on the moraine, suggests that the function of the mound, initially at any rate, may have been industrial. The reconstructed archaeological evidence suggests that the last structure on the mound was a stone-based tent/hut more suited to interpretation as a domestic site than a tryworks. By the 1870s and 1880s the mound provided a convenient structure for siting a living hut, and it is the remains of this perhaps secondary structure that have survived.

At Spit End, the living huts were located up on the moraines, often in the lee of large boulders. All the huts recorded in 1986–87 by McGowan and Lazer had a rectangular floor plan, with the exception of one of the Sealers Beach huts which may have been L-shaped. Burton & Williams (1985) reported one round and two elliptical structures at South West Bay Beach. This type of hut has not been found elsewhere at Heard Island and the date of this site is uncertain. Small, low, circular stone structures have been reported from Prince Edward Island, where they have been interpreted as Macaroni penguin holding bays (Cooper & Avery 1986: 22 and fig. 10). Only one of the huts examined, the L-shaped hut at Sealers Beach, seemed to be internally divided into rooms. Sizes range from 15.5 m x 10 m at Sealers Beach to 4 m x 3.25 m at Saddle Point.

At Sealers Beach we recorded the remains of three large huts close to each other. These huts consisted of stone footings with wooden upright posts (figs 8, 9, pl. 5). The large quantity of fallen wooden boards inside these huts indicated that the walls were made of boards fixed to the wooden uprights. Possibly the roofs were made of wood also, or they may have been thatched or covered with sailcloth or skins, which probably would have left little archaeological evidence. The eastern hut may have been partly floored with cobbling. The central hut had two porched entrances, half-way along the west wall and on the south side. Both entrances had external stone porches, which were built as a protection from the weather. A similar porch constructed of turves was described for a hut built from an upturned boat on Kerguelen Island (Nunn 1850: 217):

> We were anxious to build out the walls, one on each side of the doorway, as we found these effectual in defending us from the storms of hail and snow to which we were always subject in this ungenial clime.

The huts on the northwestern beaches of Heard Island were generally smaller and were typically stone-wall huts lined with wooden boards or planks. This construction was seen most clearly at Corinthian Bay. The hut was built in the second half of the 19th century but was also used during the second sealing period in the 1920s. It was probably renovated at this time, as the first ANARE expeditioners remarked on its good state of preservation (Scholes 1949: 95–96). The stone walls were between 1 and 2 m thick enclosing a rectangular wooden hut 3.5 m x 4.5 m with a single pitch wooden roof. Scholes also mentioned the use of corrugated iron. A photograph taken in 1902 by E. Vanhoeffen and published by Drygalski (1912) showed the stone walls rose to two-thirds the height of the hut. A gap in one wall formed a small internal porch allowing access to the hut door. This hut did not have a chimney, although in 1948 a stove was reported inside. The huts at Red Island and Saddle Point also seemed to follow this design, with some evidence of stone footings with an internal wood lining, although in 1986–87 there were no surviving standing walls.

Other domestic sites, at Try Pot Beach and Spit Bay North, were indicated by scatters of domestic artefacts, although any obvious structural evidence had disappeared. Both sites must have had huts but have been so disturbed that any evidence of their form is gone, although dressed and moulded timber was found at both sites in 1986–87.

The archaeological evidence indicates that sealers' huts were more substantial than might be thought likely from contemporary descriptions of the living conditions. The crew of Captain Robinson's Tasmanian ship *Offley* arrived at Heard Island in 1858 expecting to live in tents. Unfortunately the supply tender carrying their tents and tools was lost, so the crew was forced to build shelters with whatever came to hand.

> Spare oars were used as roof beams, seal skins were used as roofs and tents made from sails and tarpaulins.

In a perhaps exaggerated account which was written by several of the crew for use in a lawsuit against the ship's owners, the building of their "miserable abode" was described thus (Crowther 1943: 553):

> We were ordered on shore upon an island covered with ice and snow and with snow falling. At length we succeeded in finding some old portions of a wreck and managed to erect a place large enough for us to crawl into. We were fully two days in erecting these few poles and a sail over them where we had to exist for upwards of six months, huddled together far worse than sheep, our fireplace tussocks of grass and our fuel Elephant's blubber and penguin skins.

Of the living conditions at Spit Bay, Captain Robinson said (Crowther 1970: 307):

> ... the men's huts were very dirty and smoky; penguin blubber, or any kind of blubber, is the only fuel used, no chimneys to the huts that I can remember.

None of the huts recorded in 1986–87 appeared to have a chimney, except perhaps one of the Sealers Beach huts, which has an iron "Pacific" stove set into a bay in one corner.

All the stone-based hut sites are thought to date from the second half of the 19th century. Many of the sites have artefact or documentary evidence of construction or use at that time. Some huts, such as the Corinthian Bay hut, were re-used in the 1920s. The only hut known to have been built in the 1920s is Admiralty Hut built by sealers for the British Admiralty at Atlas Cove (Keage 1981:14). It is a small six-sided hut, built entirely of wood and is very different from the much larger and earlier stone-based huts (pl. 6). It had a stove and a stove-pipe chimney, which operated so inefficiently that when it was lit the door had to be left open for ventilation (Fletcher 1984: 95).

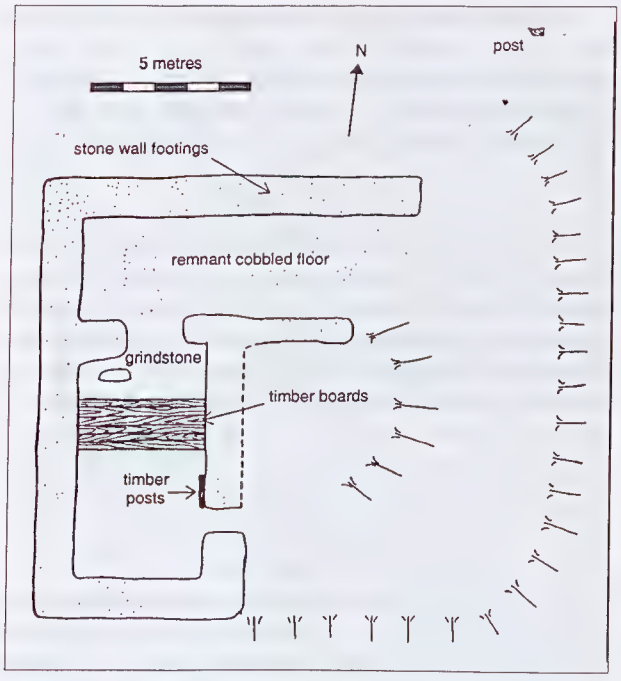

FIG. 8 — Plan of eastern hut at Sealers Beach, Heard Island 1986–87.

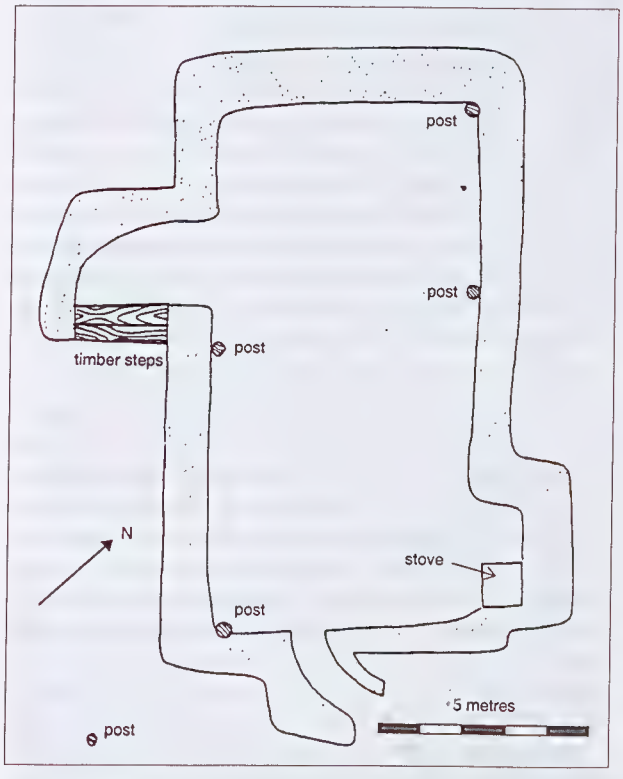

FIG. 9 — Plan of central hut at Sealers Beach, Heard Island 1986–87.

The first recorded group of sealers to winter at Heard Island, in 1856, are said to have lived in square holes dug in the ground and covered with wooden boards, moss and snow (Lanman, quoted in Law & Burstall 1953: 2). Moseley, from the 1874 *Challenger* expedition, also found sealers living in holes under wooden roofs (Moseley 1879:

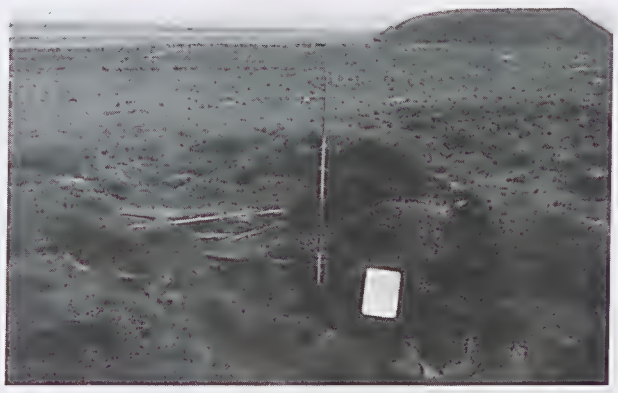

PLATE 5
Remains of eastern sealers' hut at Sealers Beach.

PLATE 6
Remains of Admiralty Hut, Atlas Cove.

229). Anne Robb found a pit hut adjacent to the standing Corinthian Bay hut ruins in 1987–88 (Robb 1988: 155).

Occupied Caves

Many lava caves occur around Heard Island. One at Red Island and a cave in a moraine at Long Beach had evidence of occupation. Another hut site at Red Island was located in the shelter of a lava overhang.

Both the occupied caves are small, 4 m deep at the most, and both contained items of structural timber, showing that their sheltering properties had been improved upon. The date of the Red Island cave occupation is unclear but it may have been used during both sealing periods. The Long Beach Cavern was a landmark that was well-known to the sealers in the late 19th century, being marked on an American sealers' map of "Hurd's Island" (sic) (Bertrand 1971: 234). It is big enough to protect about three people from the worst of weather.

Not surprisingly, sealers have always been ready to take advantage of the natural shelter offered by caves, and this type of occupation is also found on other Subantarctic sealing islands. Sealers occupied two caves on Marion Island, both of which had substantial stone walls at their entrances Two rock overhangs also provided shelter and contain equipment and camp refuse (Cooper & Avery 1986: 17, 19). Three occupied caves with stone or earth walls and two overhangs with timber, equipment and tent debris were reported from Prince Edward Island (Cooper & Avery

1986: 19, 23). Caves were used by shipwrecked sealers and later expeditions on Macquarie Island (Davies 1982, Townrow 1989: 124–125).

LIVING AND WORKING ON HEARD ISLAND

To a certain extent it is possible to argue which sites on Heard Island were used primarily for domestic and which for industrial purposes. These functions have been identified primarily on the basis of the structures of the sites themselves and the diagnostic artefacts found associated with them. Descriptions and identifications of the artefacts recorded at the sites together with a preliminary analysis of these material culture remains, was undertaken by Estelle Lazer and was reported in detail in Lazer & McGowan (1989: 39–59). The following types of artefacts have contributed to identifying the function(s) and date of use of the sites: trypot, ammunition, scrap blubber press, butchered seal bone, copper oil cooling tank, blubber skimmer, blubber fork, lance, hook, iron bar, barrel, axle, tryworks hearth, grindstone, cast iron stove, clay smoking pipe, domestic ceramics (plates, bowls, jugs), bottle glass, knife, clothing (boot, shirt, buttons), copper and iron nails, wooden floors and posts.

On the northwestern side of the island, the functional differences of the sites appear less clear cut. Where site functions can be distinguished, it appears that the working areas were very close, if not adjacent, to the living huts. For example at Corinthian Bay trypots and an extensive scatter of artefacts including sealing equipment and domestic pottery were found within 20 m of the hut.

At the Spit end of the island, there seems to have been a clearer separation between living and work areas. In general, the work platforms are down near the beach and constructed so as to overcome the environmental disadvantages of that location. The living huts are up on the moraines, often in the lee of large boulders and above the worst of the seal wallows. However, some industrial activities seem to have been undertaken on the moraine at Sealers Beach, as evidenced by the presence of a number of sealing artefacts including pieces of trypot up there. At Long Beach, a stone work platform may have been re-used by the last sealing party to stay there as a domestic hut, although the evidence for function here is inconclusive.

At the southeastern end of Heard Island, we found a series of working platforms on the beaches and a number of domestic sites on the moraines. In most cases I would not like to link particular working platforms with particular living huts. However, at Sealers Beach, it seems that the group of three huts on the moraine must be associated with the tryworks below. Although badly damaged by seals, there was enough left of the layout of the site for a thorough survey of artefacts, from which it would probably be possible to determine activity areas on the moraine. Does the arrangement of the three huts represent a chronological progression, contemporary functional differences or contemporary social differences?

I would argue that the two sets of sites, at the northwestern and eastern (Spit) ends of the island, are sufficiently dissimilar in character to suggest differences in the way the industry was operating. On the northwestern beaches, there appears to have been a wide variety of domestic architectural forms, including rectangular wood-lined stone huts at Corinthian Bay, Red Island and Saddle Point, pit dwellings at Corinthian Bay, elliptical stone-based huts at South West Bay and modified caves at Red Island, as well as the six-sided wooden Admiralty Hut at Atlas Cove. At all locations where there are diagnostic artefacts and structures, domestic and industrial functions were either located very close to each other, or there does not appear to be a specific separate industrial area. This suggests to me a pattern arising from a number of individual operations, which did not have much contact with each other or at least not enough contact to share a common vision of the way things should be done. These different styles of sites may have been built and used by sealing gangs that were from different ships, most likely in different years, and possibly in competition with each other. These camps were probably used and re-used over longer periods of time. The last sealers to work on Heard Island, the Kerguelen Sealing and Whaling Co., were based at Atlas Cove in the 1920s, where they left various items of equipment branded with their name, used the Corinthian Bay hut and were engaged to construct the small wooden Admiralty Hut.

On the eastern, Spit End, beaches, the sites show such strong formal similarities (especially in comparison to the stylistic anarchy of the northwestern beaches) that I would argue that they almost certainly resulted from the same (or at least related) operations. Firstly, the distribution of the sites appears to demonstrate a clear and consistent separation between the industrial and domestic areas, with the tryworks located down on the beaches and the huts located up on the moraines. The tryworks themselves also show a strongly shared formal style. All were constructed on stone platforms, an architectural style which appears uniquely characteristic of this suite of sites. The high level of similarity between the sites at Spit End suggests that these sites were not only built (or more likely rebuilt from earlier structures) and operated by the same (or closely related) groups of sealers, but they were not reoccupied and altered subsequently. That is, the last sealing expedition to operate in this part of the island operated in a co-ordinated manner on a large scale across the whole of this end of the island, rather than comprising a number of smaller unrelated or rival operations. There is no archaeological evidence that this part of the island was reworked by sealers in the 1920s.

This suggestion makes this suite of sites at Spit End particularly valuable, firstly for their ability to provide rich material for a study of contemporary intersite variability, and secondly because this enables the sites, their technology and the period of use of their material culture to be reasonably accurately dated. The last documented sealing expedition at this end of the island took place in the 1880s when the *Trinity* was wrecked. The shipwrecked crew were marooned for 15 months from October 1880 to January 1882 (Bertrand 1971: 251–252, Busch 1980: 121). The archaeological evidence is that, during this time, they constructed a substantial camp on the moraine above Sealers Beach and continued to work the Spit End beaches systematically, right up to the moment of rescue. The large cache of full barrels abandoned at Oil Barrel Point suggests that, when rescue came, the sealers were not really prepared. It is unlikely that they would have abandoned this valuable cargo unless conditions were exceptionally bad. Perhaps the captain intended to return later to pick them up, but no-one ever did.

FUTURE RESEARCH POSSIBILITIES

In conclusion I would like to suggest a number of specific interpretation frameworks for archaeological research at Heard Island, all of which are fundamentally related to the theme of isolation.

Changes in technology and industrial processes

A range of movable artefacts and structures have been recorded associated with sealers' sites on Heard Island. Relating these to the two documented periods of sealing activity, may provide the opportunity to trace technological progress in the sealing industry over some 80 or more years. The unique stone working platforms are items of particular interest.

Social separation and isolation

How did the sealers' society function on the island in the light of these and other social issues?

For example, we know from documentary sources that the sealing gangs on Heard Island contained some discrete ethnic groups who were said to be living separately. These groups included Americans and Africans, who were known generically as Cape Verde Islanders (because this was where they joined ships' crews as a means of gaining passage to America). Race was fundamental to their social relations, and different ethnic groups occupied separate quarters, at times racial tensions flaring (Busch 1985: 175–179). The intra- and intersite distribution of specifically American or African/Cape Verde/Portuguese artefacts may provide information about the relationships between different ethnic groups, enabling the degree of social separation inferred from historic sources to be tested and/or demonstrated. In a more general sense, such an approach could examine the potential of the archaeological record to determine social arrangements and status within a community. Taking this idea further, the archaeological expression of ethnicity on Heard Island could then be compared to other sealing communities with distinctive ethnic groups, such as the Bass Strait Islands, which comprised American and British men and Tasmanian Aboriginal women.

Another example: Subantarctic sealing communities were very male societies. Only one woman, a captain's wife, is recorded as having made a very brief visit to Heard Island. Comparison of the archaeological remains of these exclusively men's camps with mixed sealing communities such as those on the Bass Strait islands may provide the opportunity to contribute to gender studies based on the historical archaeological record.

Economic history

The 19th-century sealing industry was a global enterprise, based initially in Britain and America and later in the colonies, and conducted on the widely dispersed shores around the Southern Ocean. The markets for seal products were in America, Europe and China, and provided those captains who survived the hazards with enormous profits. Archaeological remains on Heard Island and other sealing regions have the potential to contribute to broad questions concerning the organisation of the sealing industry, the technology and the international commercial networks.

Colonisation of the world

This is one of the great recurring themes in archaeology. The remote sealing settlements, such as those found on Heard Island, have a great potential to contribute to this discourse. In my opinion we should view these communities as temporary outposts, remote and isolated from their economic and cultural focus, rather than pioneers of colonisation. These Subantarctic sealing communities clearly never intended to establish themselves as colonies. They never (or at least rarely) included women, were always short-lived and concentrated their economic activity on accumulating huge quantities of resources for removal rather than following a long-term subsistence strategy. As such, these settlements provide an archaeological contrast to the remains of both successful and unsuccessful colonisation attempts elsewhere, perhaps enabling the archaeological characteristics of pioneer colonising settlements to be more readily recognised.

CONCLUSION

If I were asked to sum up the archaeology of Heard Island in one word, I would say it was about "isolation". Heard Island (with perhaps other sealing islands in the Subantarctic region) offers the opportunity to study the archaeology of communities in isolation and this is the fundamental theme underlying its history and archaeology:

– its enormous geographical isolation;
– the consequent isolation of a commercial product from its markets;
– the isolation of remote outposts of society far from home and the source of all supplies;
– the physical separation of the gangs around the island from each other by huge rivers of ice;
– the isolation of men from the society of women;
– the social isolation of different ethnic groups, even in the face of dire circumstances or perhaps because of it, as a way of maintaining a cultural link with the mores of home.

Study of the material cultural remains on Heard Island has the potential to significantly contribute to the development or discussion of all these issues — and doubtless more.

The largest and best sites are fast disappearing along with all their information, their potential for understanding the history of a major 19th-century global industry and their wonderful collection of objects. This is a crisis situation, probably the single most serious issue currently needing to be addressed on Heard Island.

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IMPORTANCE OF "HISTORIC SITES" ON HEARD ISLAND FOR PROTECTION OF SCIENTIFIC RESOURCES AND ENVIRONMENTAL MANAGEMENT OF A WORLD HERITAGE SITE

by Janet Hughes and Estelle Lazer

(with two tables and five plates)

HUGHES, J. & LAZER, E., 2000 (30:vi): Importance of "historic sites" on Heard Island for protection of scientific resources and environmental management of a World Heritage site. *In* Banks, M.R. & Brown, M.J. (Eds): *HEARD ISLAND PAPERS. Pap. Proc. R. Soc. Tasm.* 133(2): 71–77. ISSN 0080–4703. National Museum of Australia, GPO Box 1901, Canberra, ACT, Australia 2601 (JH) and Department of Archaeology, University of Sydney, NSW, Australia 2006 (EL).

Heard Island has important historic sites relating to the hunting of elephant seals and various scientific activities, which are noted in the World Heritage citation for the island. Some, especially sealing sites, are generally acknowledged to have historic value, but the value of later sites, such as the first ANARE base at Atlas Cove, is debated, due to its recent date, unattractive appearance, rapid deterioration and hazards to wildlife. The authors believe that Atlas Cove is significant to Australia's Antarctic history, but this does not necessarily require that all elements of the site must be preserved *in situ.*

The potential historical value of this site is briefly reviewed; the value of comparative studies of historical, archaeological and materials conservation information on historic sites on other Subantarctic islands is also considered.

Documentation of these aspects of the sites is essential, certainly before any "clean up" is carried out at Atlas Cove since it will produce information to assist in environmental management and may benefit scientific research. Identification of the scientific artefacts and achievements should be an essential part of documentation of Subantarctic sites, but generally has not been given significant attention by archeologists. For development of a statement of significance for Atlas Cove, it is vital.

Key Words: historic site, sealing, ANARE, Atlas Cove, Spit Bay, scientific significance, historic significance, hazardous materials, archaeology, materials conservation.

INTRODUCTION

This paper aims to review the location, extent, characteristics and significance of historic sites on Heard Island and is based on fieldwork carried out by the authors during 1986–1987 (Lazer) and 1992 (Hughes). The purpose of the review is to examine values relating to historic buildings and associated artefacts in both the historic and scientific context and, through this, to develop significance criteria against which to consider the need for preservation of the sites. Preservation involves a consideration of materials conservation issues because of the severe, maritime conditions of Heard Island.

PLATE 1
The remains of the Admiralty Hut and adjoining ANARE Surgery at Atlas Cove (February 1992).

HISTORY OF HEARD ISLAND

Discovery and Early Exploitation of Heard Island

The date of discovery is still the subject of investigation (Allison & Keage 1986, Lazer & McGowan 1990: 9–11), since it is possible that the island was known before its recorded discovery in 1855 by Heard, an American sealer. Elephant sealing was conducted during the 19th and early 20th centuries at various sites on the island, with most activity at the Spit Bay end of the island. The sealers were predominantly American but also included significant numbers of Cape Verde Islanders (Starbuck 1878).

Early Scientific Expeditions

Scientific expeditions, such as that of HMAS *Challenger* (1872–76), the German *Arkona* (1874) and Drygalski's *Gauss* expedition (1901–3), visited the island, usually in conjunction with oceanographic cruises (Headland 1989). The *Challenger* expedition conducted extensive oceanographic studies, including sampling the ocean floor around the island (Tizard *et al.* 1855). A microscope slide of sediment from the ocean floor in this region is displayed at the Australian National Maritime Museum in Sydney. The hexagonal "Admiralty Hut" (pl. 1) was built in 1926 by the crew of the *Kildalkey* and appears to have been used by a number of expeditioners, including Aubert de la Rue (Law & Burstall 1953: 5). The British, Australian and New Zealand Antarctic Research Expedition (BANZARE) stayed for approximately one week in the Admiralty Hut in 1929,

while carrying out a range of scientific observations (Fletcher 1984, Jacka & Jacka 1988).

These scientific visits had minimal enduring impacts, since few stayed long enough to establish buildings and they did not harvest large numbers of wildlife. Their descriptions, photographs and maps provide useful information for subsequent scientific study.

ANARE PERIOD

The Australian National Antarctic Research Expedition (ANARE) base at Atlas Cove in 1947 was the first one established by Australia during the "modern" era of Antarctic exploration. Heard Island was formally claimed at this site for the British Commonwealth. Following an "exchange of notes" between Great Britain and Australia in 1951, the sovereignty of Heard Island was transferred from Great Britain to the Australian Commonwealth (Law 1983: 44). Important scientific research was conducted during the ANARE occupation between 1947 and 1955 (pl. 2). This included geology, biology (seals, birds, parasites, insects and arachnids, fish, plankton and hydrology, botany, algae and marine fouling), meteorology and physics (cosmic rays, geomagnetism, seismology, aurorae), listed in Law & Burstall (1953).

Approximately 25 buildings were constructed at Atlas Cove to provide accommodation for expeditioners and for scientific activities (Law 1983); a full list of these is contained in Jongens (1983). The construction of the buildings reflects attempts to select materials and design features suitable for the cold climate and severe winds.

HUMAN IMPACTS OF EARLY OCCUPATIONS OF HEARD ISLAND

Introduction

Since protection of Heard Island's scientific and environmental values is a key objective for a World Heritage place, it is useful to consider the island's history in terms of past "human impacts" on the environment. This approach focuses attention on past human activities on the island to analyse their current significance, for example, depletion of wildlife by sealing and scientific activities. Wildlife exploitation had a major impact on all Subantarctic islands. Large numbers of elephant seals were killed during the 19th and early 20th centuries. It was common for whole beaches of seals to be slaughtered by sealing gangs (Fletcher 1984).

Evidence of past introductions of alien domestic species includes bones of dogs and sheep. These species were deliberately introduced to the island for various purposes (including dogs for transport and sheep for food) although fortunately none has survived. Johanson (1992) showed the high risk of introduction of alien species, especially plants, via human travel between neighbouring islands.

All of these have ongoing significance in the World Heritage context. Other past human impacts include abandoned buildings and equipment which present physical hazards. Oil, chemicals and toxic or hazardous materials are chemical contaminants which may persist in the environment. There are many rusty ANARE fuel drums at Atlas Cove (pl. 3), several of which were found to contain oil during the ANARE visit by Hughes (1992). Leakage

PLATE 2
The remains of the ANARE station at Atlas Cove (February 1992).

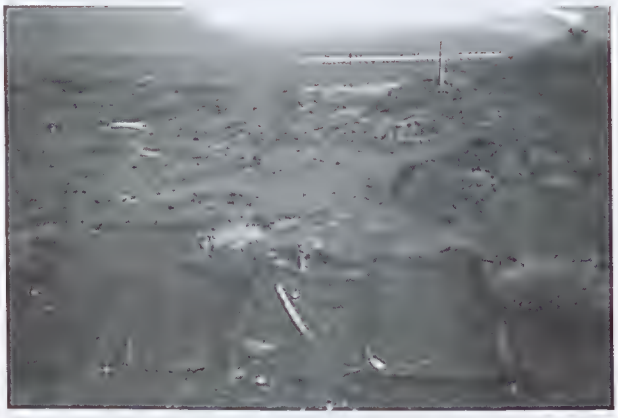

PLATE 3
Remnants of steel oil drums near the ANARE Surgery at Atlas Cove. These have been "cut off" above ground level by a combination of abrasion by scoria particles and corrosion, leaving jagged edges (February 1992).

was evident where some drums had stood. Other chemicals included anaesthetic ether (among numerous medical items in the old Surgery) and some fibrous lagging material which may contain asbestos. From their fieldwork on Heard Island, the authors have identified several types of potential scientific information which should be investigated before any "cleaning up" is attempted. Evidence of past human impacts may provide valuable information on the extent and content of buildings, the materials used and the location and context of any hazardous materials, for example, the possibility of asbestos and polychlorinated biphenyls used in electrical and heating equipment .

Given the rapid deterioration of the old station, the need for documentation of the buildings and past human impacts is urgent. Even after the site is "cleaned up", it is important to know the former location of buildings and artefacts to account for any subsequent effects, particularly where pollutants may affect the subject of scientific studies, such as the growth rate of vegetation.

Archaeologists are the appropriate professionals to undertake excavation and documentation of the old ANARE site. They frequently work in multidisciplinary teams and

even for such a recent site as Atlas Cove, their work has the potential to provide invaluable information which will benefit future research and environmental management of the island.

Other research which indicates the potential usefulness of the examination of historic artefacts includes the work of Downes (1989) in studying logbooks of the voyages to Heard Island and measuring oil barrel staves recovered there to calculate barrel volume and, hence, volume of seal oil harvested. This information can help to estimate the economic and environmental impact of past wildlife exploitation. Smith *et al.* (1989) presented a case for collaboration between various scientists and cultural heritage specialists to study driftwood on the island. Research by Lazer & McGowan (1990) allowed documentation of sealing information over the entire island, as well as information about the killing and processing of the elephant seals. Thus, archaeological study of Atlas Cove has the potential to provide further knowledge about the extent of impact of human activities and identify which impacts may be persistent, knowledge which will assist ongoing environmental monitoring.

Archaeological and Materials Conservation Research Required Before "Clean Up"

Archaeologists and conservators have complementary roles in working together on cultural heritage sites. The archaeologist studies the physical evidence of the site, analyses the evidence of historic activities which took place at the site and interprets its historical significance. The conservator uses this analysis to decide priories for preservation of the artefacts (which may include whole buildings) and also identifies the appropriate conservation methods.

Archaeologists' activities may include bibliographic research, a photographic survey of sites, description of significant features and recording of any excavations. Measurement of significant features and their spatial arrangement is used to determine the extent of the site and provide a site map. The data is analysed to produce a statement of the significance of the site, and the archaeologist provides key input into development of a conservation management plan.

Conservators' activities may include photographic recording and description of the condition of significant features of the site(s), identification of mechanisms and measurement of rates of deterioration, and determination of priorities for conservation. Standard conservation techniques may be used, but the severe Subantarctic conditions of Heard Island may also necessitate development of new preservation treatments or removal of items to Australia for treatment, subject to appropriate approvals.

Stabilisation of artefacts and building materials or of objects exposed during excavation is important as deterioration generally increases upon exposure. A monitoring programme is produced for sites and artefacts to determine the longer term efficacy of conservation treatments and to identify the need for any further stabilisation. The conservator joins the archaeologist in providing input into the development of a conservation management plan.

Sources of Archaeological Information on Subantarctic Islands

All Subantarctic islands share the same historical pattern of exploration of the southern oceans leading to exploitation of the seal populations. Thus, cultural heritage studies of Subantarctic sites other than those on Heard Island are relevant, since they also contain evidence of sealing activities and early scientific bases comparable with those of Heard Island. Sites on other Southern Indian Ocean islands (Marion and Prince Edward Islands, Îles Kerguelen, Îles Crozet) are particularly relevant, because of elephant sealing activities by the same ships and often the same gangs as operated on Heard Island (Cooper & Avery 1986, Downes 1996). The ANARE base on Macquarie Island was established only a few months later than Atlas Cove, and useful comparisons may be made with building design, equipment and activities undertaken by occupants. Some Arctic island sites, such as Jan Mayen, Svalbard and Franz Josef Land, may be relevant to Heard Island in considering adaptation to isolated locations with severe climates. Some similar activities took place (scientific exploration, sealing, whaling), but most of the historic sites in the Arctic are of much earlier dates, with some sites on Svalbard dating from the 17th century.

TABLE 1
Archaeological publications on relevant Subantarctic sites

Location	Activity relevant to Heard Island	References
Heard Island	Sealing, exploration, shipwreck, ANARE base	Burton & Williams 1985, Robb 1987/88, Lazer & McGowan 1990, Downes 1996
Marion & Prince Edward Island	Sealing, 1940s scientific bases	Cooper & Avery 1986, Graham 1989
Îles Kerguelen & Îles Crozet	Sealing, exploration, shipwreck, whaling	Le Mouël 1994
Macquarie Island	Sealing, 1940s ANARE base	Davies 1982, Townrow 1988
Auckland/Campbell Island	Sealing, exploration, shipwreck	Judd 1992
South Georgia	Exploration, shipwreck, whaling	Basberg *et al.* 1996

Relevant studies of historic sites carried out on several Subantarctic islands include detailed site surveys and excavations, with those on Marion Island, Iles Kerguelen, Macquarie Island and South Georgia receiving the most detailed investigation. Sealing sites on Heard Island were studied by Burton and Williams in 1985 (Burton & Williams 1986) as a ground survey. Lazer and McGowan visited sites 1–35 (listed in Lazer & McGowan 1990) and excavated one sealing site at Oil Barrel Point (near Spit Bay). It was not possible to visit sites 36–46 near Atlas Cove. A few artefacts of particular interest were brought to Australia, including a unique blubber press, now held by the Queen Victoria Museum in Launceston.

Development of Significance Criteria for Abandoned Sites

Determination of significance criteria is a standard and essential requirement for assessment of any site of potential historic significance. They are derived from the historical context of the site. Warren (1989) proposed significance criteria for historic sites in Antarctica. The authors have adapted these, with slight variation, for abandoned Subantarctic sites:

(1) an important event or activity took place at the site, or the site typifies a significant relevant period of activity;
(2) a significant scientific discovery or innovation occurred;
(3) a significant death or deaths occurred;
(4) evidence of sovereignty is present;
(5) there is material evidence of a unique lifestyle or response to the severe environment.

A brief and simplified example of how these criteria might be applied for Atlas Cove is given below, although detailed investigation may reveal additional information.

(1) Atlas Cove was the site of the first ANARE station, which was a significant event in Australia's Antarctic and Subantarctic history.
(2) Important cosmic ray studies, commenced on this site, improved knowledge of upper atmosphere physics and led to subsequent studies in Antarctica.
(3) Two ANARE expeditioners lost their lives during the occupation of the ANARE base and they are commemorated by a small memorial.
(4) The ANARE station is physical evidence of Australian sovereignty, by virtue of occupation during 1947–55 and scientific activities carried out on a regular basis since that time. The prior British occupation of the site is evidenced by the Admiralty Hut, later extended by ANARE.
(5) The distinctive polygonal huts and other buildings were part of the trial of building materials and designs which was essential preparation for the founding of proposed "permanent" bases on the Antarctic continent (Scholes 1951). This is of interest in showing how Australians proposed to develop existing technology to cope with cold, remote conditions, which are largely unfamiliar in Australia.

Atlas Cove is often considered to be a site which is so recent that it cannot have historic significance, yet age alone is not a good indicator of cultural significance. The site has some potential cultural and scientific significance, although this does not necessarily require that all material comprising the site must be preserved: such an assessment should not be made until a framework for archaeological and conservation assessment has been developed and approved by relevant Australian government agencies.

Materials Conservation

While there are few sources of archaeological information for sites on Heard Island and other comparative Subantarctic islands, there are even fewer sources of conservation data or comparative research for any Subantarctic island. Observation by Hughes during a brief visit to both Atlas Cove and Spit Bay during 1992 produced some photographic records detailing condition of buildings and artefacts such as trypots (pl. 4) and oil barrels.

Deterioration processes affecting Heard Island sites

A number of factors are causing deterioration of the historic sites on Heard Island and these are particularly destructive when operating in combination. Wind has caused structural damage, particularly affecting the buildings at Atlas Cove. The low walls, which are all that remain of most of the sealing huts, do not present a large profile to the wind. Wind picks up abrasive particles that cause "corrasion" or erosion of surfaces. Water and high humidity result in frequent wetting and drying cycles, which promote swelling and cracking of wood. The maritime climate promotes corrosion, and temperatures are sufficiently high to allow biodeterioration. Salt deposition also causes "defibring" of timber, during which wood fibres separate from the surface of the timber, resulting in progressive reduction of structural strength.

Wallowing and rubbing by wildlife is evident in some buildings at Atlas Cove and also affects the remaining oil barrels at Oil Barrel Point. Humans have removed and relocated artefacts and buildings, particularly at Atlas Cove. While few tourists have been able to land on Heard Island, the impact of tourism is potentially significant, since the few tourists who have visited have strongly lobbied for the removal of the ANARE buildings, due to their adverse aesthetic impact. Coastal erosion is occurring rapidly, particularly along the southern and western coasts of Heard Island. The Oil Barrel Point historic site is useful for monitoring the progression of erosion of the beach (M. Mabin, James Cook University, pers. comm.).

The ANARE buildings have now severely deteriorated and fragments are being blown about the area, which is a significant breeding area for seabirds and much frequented by penguins and seals. Photographs taken during ANARE occupation in 1947–55, 1987 and 1992 show the

PLATE 4
A sealing site at Spit Bay with trypots in situ *(February 1992).*

progressive destruction of the buildings. These and additional photographic documentation by Thornton (1983), during an expedition to climb Big Ben, and by Hughes in 1992 are sufficiently detailed to allow the rate of deterioration of structures at Atlas Cove to be quantified.

Materials conservation data

Less information is available on conservation of historic sites in Subantarctic conditions than in Antarctica, where several studies on building and materials deterioration have been undertaken since the 1980s. A bibliography of relevant conservation research for both Antarctic and Subantarctic sites has been compiled by Hughes and awaits publication. Data on deterioration of materials relevant to conservation of Subantarctic sites include some corrosion-rate information and some field applications of timber preservatives applied to Stella Hut on Enderby Island in the Auckland Islands (J. Fry, pers. comm.). There are few effective, long-term preservative treatments suitable for wood in Subantarctic conditions.

Corrosion rate data

Hughes *et al.* (1996) carried out an extensive survey of corrosivity (standardised corrosion rate, measuring in microns the thickness of metal corroded per year) measurements in Antarctica and on some Subantarctic islands. This includes a methodology for the measurements using a standard low copper alloy steel (which has a corrosion rate similar to mild steel, a common building material). Data were obtained for six sites on Macquarie Island (King & Hughes 1993). Weighed metal plates of standardised size ("coupons") were sent and attached to Stevenson screens in the meteorological station at Marion Island, Signy (a British base in the South Orkney Islands) and a temporary meteorological screen at Spit Bay on Heard Island. A coupon was deployed at Atlas Cove but was lost, due to the building being torn apart by the wind.

According to the ISO Standard 9223 classification, the corrosivity of steel at Spit Bay is "very severe". The longer period of exposure of the coupon at Macquarie Island has been taken into account, and the higher corrosivity rate is probably due to a combination of high salt deposition and the erosion of the coupon surface by windborne particles. The rate measured at Spit Bay is sufficiently high to conclude that conventional corrosion protection, such as galvanising and protective coatings, would be ineffective. Corrosivity at Atlas Cove is expected to be higher than that at Spit Bay due to its more exposed location and severe weather.

TABLE 2
Corrosivity rates at Subantarctic islands

Site	Days exposed	Corrosivity (m/yr)
Heard Island (Spit Bay)	341	55.3
Macquarie Island (Isthmus [Weather Station])	721	222
Marion Island (Weather Station)	376	31.9
Signy (Weather Station)	365	36.4

Further Archaeological and Materials Conservation Research Requirements for Heard Island

The need for documentation of the scientific values of abandoned bases of Heard Island

Since Heard Island has both scientific and cultural values, managers of the island should consider whether there may, indeed, be overlaps or conflicts between these values, and whether a study of early human impacts may also produce useful scientific information. This will have implications for the "clean up" of Atlas Cove and for coordination of the scientific programme anticipated in 1999–2000. Identified research questions, which should be investigated, include

- What elements of an abandoned site, even if not of historic significance, may have scientific value(s)?
- How can this information be identified during the archaeological and conservation documentation of the site?
- How should the information be recorded, analysed and preserved for long-term benefit?

There are many elements of abandoned sites that may have scientific significance which should be recorded and investigated. The precise location, description and source of information which could be re-used for scientific purposes must be recorded, for example, locations of meteorological screens, survey marks, gravity and magnetic stations, and scientific instruments such as tide gauges. The location should be precisely recorded, relative to a survey mark, so that variation over time since the original scientific study can be determined. This approach is being used at Cape Denison and Macquarie Island, where the Australasian Antarctic Expedition (AAE) bench-marks are being used to determine possible change in sea-level relative to tide gauge readings made by the AAE (R. Summerson, Bureau of Rural Sciences, pers. comm.).

Soil stratigraphy revealed during excavations may assist in dating characteristics of past soil and vegetation disturbance, e.g. datable artefacts may be used to identify soil horizons. Vegetation growing on areas of past disturbance allows measurement of long-term plant growth rates.

Datable animal remains (such as seal oil and bones) can help in determining baseline environmental levels of natural substances and pollutants such as heavy metals, radioactive elements and pesticides. Retention of "historic fragments", such as lichen growth on stone comprising a sealing platform, can assist in dating processes. Features such as Oil Barrel Point (pl. 5) are useful in dating coastal erosion processes (M. Mabin, James Cook University, pers. comm.).

Documentation of "rubbish" potentially provides information on the extent and type of environmental pollutants. For example, knowledge of the building construction materials used may allow identification of possible hazards such as asbestos and polychlorinated biphenyls.

Success has been achieved in utilising scientific information at a variety of cultural sites in polar regions, especially Inuit human remains at Qilakitsoq in Greenland (Hansen *et al.* 1985), whaling sites on Svalbard (Hacquebord 1988) and, to a limited extent, at Cape Denison in Antarctica (Hughes & Lazer, pers. obs.). Most of these studies have considered analysis of material recovered from the site rather than anticipating sources of information which can be recorded and integrated into long-term scientific monitoring and recording in the field. There have been few opportunities thus far to develop these research

PLATE 5
Oil Barrel Point, Spit Bay, showing the weathered remains of seal oil barrels laid on their sides. The site is rapidly being eroded by the sea (February 1992).

opportunities and to integrate these studies into conservation management plans for historic sites.

The need for analysis of the sites

The comprehensive and accurate analysis of the potential scientific and historic resources of Heard Island sealing sites and at Atlas Cove require priority support. Such analysis requires

- appropriately trained cultural heritage professionals, preferably with a strong background in the history and philosophy of science relating to Subantarctic history and the experience and ability to work in a multidisciplinary team with scientists;
- adequate time to assemble past ANARE records for Atlas Cove;
- strong interaction with "clean up" teams (record process, location of test points, types of materials expected); and
- adequate assistance for GPS, aerial photography, surveying.

CONCLUSIONS AND RECOMMENDATIONS

- Archaeological and materials conservation data are valuable, and indeed essential, for the environmental management of this World Heritage island.
- Professional assessment of historic/scientific significance is important for all historic sites on the island including the first ANARE base at Atlas Cove (despite its recent age).
- Significance criteria for the site should be developed and agreed with the appropriate agencies.
- Scientific resources of abandoned human occupations should be investigated on all Subantarctic islands, including Heard Island.
- Removal to Australia of any artefacts revealed by archaeological investigation of sites should be carefully planned, since on site stabilisation is important to prevent damage. An appropriate institution should be sought to curate and preserve artefacts before their removal from the island.

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Access to information on Heard Island historic sites is, in many cases, difficult, since much is unpublished (such as reports or theses) or printed in journals of limited circulation. The references cited below cover all known, relevant information on historic sites; many (marked by an asterisk) are held at the Antarctic Division Library at Kingston, Tasmania. Copies of the other unpublished reports and theses are held by J. Hughes.

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